PROCEEDINGS

January 20, 21

1983

MEASUREMENT SCIENCE CONFERENCE

HYATT RICKEYS

Palo Alto, California

ACCURACY AND AUTOMATION

MESSAGE FROM THE CONFERENCE DIRECTOR

On behalf of the 1983 Measurement Science Conference, its Board of Directors and Conference Committee Members, I want to thank you for attending this, our twelfth Measurement Science Conference on January 20 and 21, 1983 at Palo Alto, California. Judging by the response on the Conference evaluation cards, you, the participants, judged the overall Conference to have been good to great by a large majority. My associates and I feel that this year's Conference was successful in its continuing role as a forum for Metrologists and all those interested in the science of measurement.

Our keynote speaker, J. David Mitchell, Director of Advance Programs and Manufacturing at Rockwell International, was well qualified to speak on "Integration Strategies - Key to Automation/Robotics." This keynote address was interesting, thought-provoking and indicative of the trend in automation in industry.

Luncheon speakers, Dr. Robert E. Larson, President of Systems Control., Inc. and Dr. Joel S. Birnbaum, Director Advance Computer Laboratories, Hewlett-Packard Company, also made excellent presentations. Dr. Larson in his discussion of "Computer Systems for Measurement Control" traced the evolution of computers and computer controlled systems as tools for measurement control. Dr. Birnbaum in his speech on "Future Interaction of Computer Technology in Instrumentation" presented some thoughts on the technology necessary for the next generation of smart instruments and a discussion of current limitations and prediction of likely trends.

The Andrew J. Woodington Award for Professionalism in Metrology was presented this year to Dr. Glenn F. Engen -- a most distinguished recipient. Dr. Engen, with the National Bureau of Standards since 1954, has pioneered many measurement techniques and standards now used in today's microwave instrumentation.

Forty-one papers were presented at this year's Conference representing a board cross section of the art and science of metrology. The selection of an award recipient of the best paper presented at the Conference is always a difficult and tedious task, and this year was no different. The "Best Paper" Award was presented to Russell Shelton - E. Leitz, Inc. for his paper entitled "High Speed Accurate Measurements on the Shop Floor".

I do want to thank my associates on the Board of Directors and all members of the Conference Committee for their extraordinary efforts which made this year's Conference a success. I also want to express my sincere appredication and gratitude to the speakers, exhibitors, session developers and to our sponsors, each of whom have contributed time and efforts to bring our Conference to you.

I hope to see you again in 1984.

Roland Vavken

Roland Vavken
Conference Director

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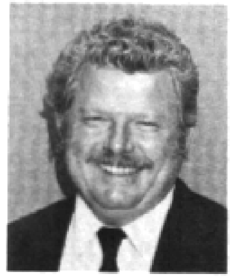

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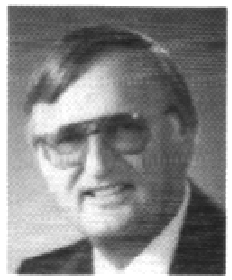

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KEYNOTE SPEAKER
THURSDAY, JANUARY 20, 1983

J. DAVID MITCHELL
BIOGRAPHICAL DATA

Dave Mitchell is Corporate Director of Productivity and Advanced Manufacturing Programs for Rockwell International. This assignment includes overall productivity planning and technical leadership in the development and application of advanced manufacturing technologies and systems.

Previous assignments within Rockwell involving both staff and line responsibilities include Senior Production Operations Executive, Director of Advanced Manufacturing Technology, and Director of Instrument Operations.

His experience includes two years as an Electronic Scientist at the National Bureau of Standards as well as key supervisory/management roles in Quality Assurance and Manufacturing for Douglas Aircraft, Litton Industries, and the John Fluke Manufacturing Company.

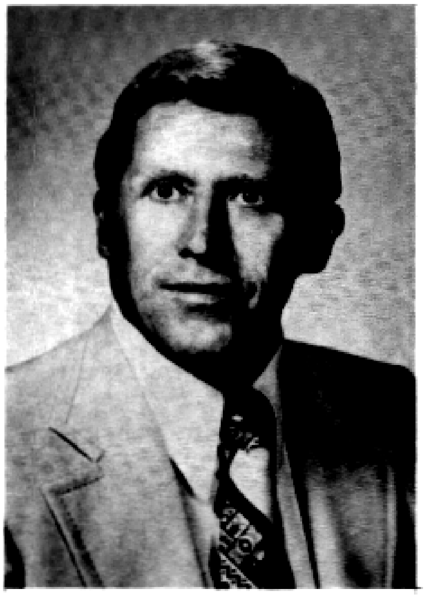
He is a member of the National Management Association and a senior member of both the Society of Manufacturing Engineers (SME) and the American Institute of Industrial Engineers (AIIE). He is a senior member and past national president of the Precision Measurements Association (PMA). He is a member of the Manufacturing Technology Advisory Group/Committee for both the Aerospace Industries Association and the Electronic Industries Association. He has participated on advisory committees for major universities and is currently a member of the Industry Advisory Organization for West Virginia University. He has also served as a member of the National Academy of Sciences Evaluation Panel for the National Bureau of Standards. He is also the past president of the National Conference of Standards Laboratories (NCSL).

- BSEE - University of Colorado
- Post Graduate Studies - University of Colorado and UCLA
- Graduate of the Executive Program - University of California
- Listed in Who's Who in the West
- Registered Professional Engineer - State of California
- Distinguished Manufacturing Engineering Achievement Award - SME 1979
- Significant Contribution to the Field of Measurement Science - William A. Wildhack Award - 1980
- Distinguished National CAD/CAM Award - National Society of Professional Engineers - 1982

He has been a strong advocate of innovative management methodologies and systems and has authored over 25 papers and articles covering a broad range of technical and management subjects in the fields of Quality Assurance, Metrology, Testing, and Manufacturing Technology.

LUNCHEON SPEAKER
Thursday, January 20, 1983

ROBERT E. LARSON



Dr. Larson received his S.B. degree from M.I.T. in 1960 and his M.S. and Ph.D. degrees from Stanford in 1961 and 1964 respectively, all in Electrical Engineering.

His fields of specialization are dynamic programming, applications of control and estimation theory, and distributed data processing. He is the author of State Increment Dynamic Programming (1968), Principles of Dynamic Programming, Vol. I (1977), Principles of Dynamic Programming, Vol. II (1982), and Distributed Control (1979). He has also written over 140 technical papers.

In 1968, Dr. Larson and two colleagues founded System Control, Inc., in Palo Alto, California, where he is currently serving as President. He previously worked at IBM, Hughes Aicraft, and SRI International. Since 1973, he has also been a Consulting Professor at Stanford University.

Dr. Larson has received several awards for his work, including the IEEE Group on Automatic Control Best Paper Award in 1965 and the 1968 Donald P. Eckman Award for outstanding achievement in the field of automatic control from the American Control Council. He was named the Outstanding Young Electrical Engineer for 1969 by Eta Kappa Nu, and he became a Fellow of IEEE in 1973.

Dr. Larson has been very active in the IEEE. He has served the IEEE Control Systems Society in a number of capacities, including President in 1975 and 1976. He was IEEE Division I Director in 1978 and 1979 and IEEE Vice President for Technical Activities in 1980 and 1981. He is President of IEEE during 1982.

LUNCHEON SPEAKER
Friday, January 21, 1983

Dr. Joel Birnbaum, Director
Computer Research Center
Hewlett Packard laboratories

SOME OPPORTUNITIES IN COMPUTER-BASED INSTRUMENTATION

Functional and economic distinctions between computer-based instruments and sensor-equipped computer systems are rapidly becoming blurred. As the technologies necessary for the next generation of smart instruments emerge, a number of fundamental assumptions are being rethought, and consideration of the implications for diagnosis, maintenance, user interfaces, interconnection, and application development are necessary. Some examples from current research will be presented, as well as some discussion of current limitations and personal predictions of likely trends.

Dr. Joel Birnbaum attended Cornell University where he received the Bachelor of Engineering Physics degree in 1960. He holds MS and PhD degrees in Nuclear Physics from Yale University. After fifteen years at the IBM Watson Research Center where he was Director of Computer Sciences, he joined Hewlett-Packard in 1980 where he is Director of the Computer Research Center in Palo Alto, California.

1983 WOODINGTON AWARD WINNER
— FOR PROFESSIONALISM IN METROLOGY —
DR. GLENN F. ENGEN

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Boulder, Colorado 80303

February 11, 1983

Mr. William Strnad
6048 Eastwood Avenue
Alta Loma, CA 91701

Dear Mr. Strnad:

There are times in life when words fall far short of the occasion. I hardly need to tell you that the MSC luncheon on January 21st was one of these times. Having partially recovered from my state of shock, and after some retrospection and reflection I have concluded that, because of what it stands for, this recognition means more to me than any other I have ever received.

You have given me a real challenge, but with God's help I trust that my life and conduct may, indeed, reflect those ideals for which this award stands.

My deepest appreciation to you and to the others who were responsible for this. I would appreciate your sharing these thoughts with them. Thank you.

Very sincerely,

Glenn F. Engen
Microwave Metrology Group
Electromagnetic Technology Division

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* Manuscript not available

Serial 21

A PRELIMINARY EVALUATION OF THE ACCURACY OF 10 VOLTS AS MAINTAINED ON THE WEST COAST OF THE UNITED STATED

Les Huntley
Dave Agy
John Fluke Mfg. Co., Inc.
P. O. Box C9090
Everett, WA 98206

ABSTRACT

The Introduction of a New Direct Volts Calibrator, which requires a 10 Volt standard for its calibration, and a New Solid State Reference Standard operating at the 10 Volt level has raised a question concerning the ability of Standards and Calibration laboratories to support 10 Volts at the accuracy level required. An experiment was performed to assess the accuracy achieved in five laboratories known to have good capability for DC and Low Frequency measurements. A spread of nearly 4 ppm in the values assigned by the labs to the transfer standards indicates that a problem exists. The performance of the Solid State Transfer Standards demonstrates their utility in achieving agreement at 10 Volts to within approximately 0.1 ppm among widely separated laboratories.

Introduction

An experiment was conducted in July, August, and September of 1982, by John Fluke Mfg. Co., Inc., in cooperation with four laboratories known to have good capability in DC Measurements, to determine the accuracy attained in maintaining Direct Volts at the 10 Volt level. There were two principal reasons for conducting the test, first, to ascertain the abilities of these and other like standards and calibration laboratories to support the accuracy of the Fluke 5440A Direct Volts Calibrator, and to demonstrate the utility of the 732A Solid State Reference Standard (735C's) recently developed by Fluke in the standardization of Direct Voltage at the 10 Volt level.

The Experiment

A transfer set consisting of two 735C of known stability was evaluated by the Fluke Primary Standards Laboratory, then was shipped to the participating labs, along with appropriate connection hardware and an instruction sheet. (The 735C is a predecessor to the 732A, differing principally in the fact that it provides only 10 Volt output.) The labs were asked to make at least three measurements of the output of each of the two standards, and of the difference between the two outputs.

Several methods were used by the various laboratories in determining the values of the 10 Volt output of the 735C's. The methods are briefly described below. The labs are identified only by letters to preserve the anonymity of the participants.

LAB A: Connected the output of the 735C transfer standard directly to the input of the ESI 722A K-V Divider having input resistance of 100,000 Ohms. With the divider set for an output of 1.018XX Volts, compared the output to a standard cell just as if it were another standard cell, using a Guildline light beam Galvanometer as the detector.

LAB B: The 10 Volt readings were obtained with an ESI 1045A potentiometric measuring system. The difference measurements were made with a Guildline 9144 potentiometer.

LAB C: Standardized 10 Volt input to Kelvin-Varley Divider against a standard cell at about 1.018XX Volts, then dialed up 10 V and compared to the output of the 735C Transfer Standard.

LAB D: Standardized 11 Volt input to Kelvin-Varley Divider against four standard cells connected in series, then dialed up 10 V and compared to the output of the 735C. Differences were measured directly, using a Fluke 845AB Null Detector.

Fluke Primary Lab: Compared output of working standard 735C to nine standard cells connected in series utilizing a freshly self-calibrated 720A Kelvin-Varley Divider and an A-100 Standard Cell Comparator. The output of each 735C was then compared to the working standard by direct measurement of the difference in output voltages using a Fuke 845AB Null Detector.

Both standards were allowed to cool to room temperature on 9 September, when they were left unplugged overnight, and SN 1009 cooled again on 14 September when the package was bumped off the plane and did not reach Seattle within the lifetime of the backup battery. While such cooling has been observed in the past to cause permanent significant changes in the outputs of these 735C's, in this case the change in output was no greater than 0.15 ppm, and had no significant impact upon the outcome of the experiment.

Results

The results of the experiment are summarized in the three figures attached. Figure 1 is a "Youden Diagram", which is obtained by plotting the value obtained by a given facility for one standard versus the value it obtained for the other standard. (Plotted here are the mean values obtained by each laboratory. The "dashed squares" are the individual laboratory's stated uncertainty, see Table 1.) The Youden Diagram has the property that positively correlated deviations cause the plotted points to be displaced along a line having a slope of +1, and negatively correlated deviations cause the points to be displaced along a line with slope of -1. Random variations tend to result in a circular distribution of points.

The most common source of positive correlation, and distribution along the upward sloping line, is systematic error in measuring the outputs. Figure 1 clearly shows such a distribution, and almost certainly indicates a systematic difference of almost 4 ppm in the value of 10 Volts as maintained in two of the labs sampled. This is a significant result in that a total uncertainty of about 1.5 ppm at 10 Volts is required to support the accuracy of the 5440A Calibrator.

Information about the stability of the outputs of the two 735C's, and information about the relative quality of the various measurement methods, may be obtained by plotting a second Youden Diagram in which the systematic variations are removed by subtracting the mean of the values obtained for the two standards from each value obtained. Such a diagram appears as Figure 2. It is immediately apparent that not all measurement methods are equally good. Both Labs B and C show a significant variability along the upward sloping line, indicating the presence of significant systematic variations in measurements of 10 Volts by that method in that lab. The distribution of points for Labs A and D is about what would be expected for purely random variability in the measurements. The points plotted for Fluke are smeared by the uncompensated drift of SN1013 relative to SN1009 over a four month time span. When this effect is eliminated, the Fluke points also appear randomly distributed.

Measuring the difference in outputs of the two 735C's directly by connecting a MicroVolt meter directly between the two outputs, has the effect of removing the imprecision in the measurement method from the determination of that difference. This in turn, allows us to monitor the relative stability of the two 735C's independently of any problems associated with measurement method, and allows an objective evaluation of the suitability of the 735C's for use in this scheme for standardizing 10 Volts. Figure 3 presents the difference data in the form (Measured Difference Minus Calculated Difference versus Julian Day). Calculated difference is used because the 735C's are not perfectly stable, and linear drifts in excess of 0.1 ppm may be expected over the time period of the experiment. With the exception of Lab A, the mean difference obtained by all the testing facilities were within a few hundredths ppm of the calculated values. Lab A did not make the measurements directly; the plotted differences were obtained by taking the differences between the measurements of 10 Volts.

The results of the experiment are summarized in Table 1. "Stated Uncertainty" is the uncertainty in the measurement of 10 Volts claimed by a given laboratory. "Difference from Group Mean" is the difference between the mean voltage obtained by a given laboratory and the mean of voltages assigned by the group of labs.

"Uncertainty in Lab value" represents 99% confidence limits on the mean of measurements made in that Lab, assuming a normal distribution of errors. That is, for example, there is a 1% probability that the true mean of the measurements at Fluke is outside the range of values bounded by plus and minus 0.015 ppm. This uncertainty, plus the uncertainty in the value of the standards due to drift, are the main components in uncertainty of the comparison of one Lab's Volt to the mean of the Group.

"Uncertainty in difference from mean" represents 99% confidence limits on the difference between a particular lab's result and the mean result of the group of five labs. It is influenced by the scatter in a labs measurement results, the number of measurements made by that lab, and the uncertainty in the mean of the group. A normal distribution of errors is assumed. It is apparent that this experiment demonstrates a powerful tool for obtaining consistency among laboratories measuring voltage at the 10 Volt level.

Table 1: Summary of Results

LAB	STATED UNCERTAINTY	DIFF FROM GROUP MEAN	UNCERTAINTY IN LAB VALUE	UNCERTAINTY IN DIFF FROM MEAN
A	0.8 ppm	-0.72 ppm	0.04 ppm	0.08 ppm
B	5.0 ppm	-1.97 ppm	0.23 ppm	0.32 ppm
C	0.6 ppm	1.16 ppm	0.20 ppm	0.30 ppm
D	2.0 ppm	1.66 ppm	0.04 ppm	0.08 ppm
Fluke	0.8 ppm	-0.12 ppm	0.015 ppm	0.07 ppm

Summary

To summarize, the experiment must be considered an unqualified success. While the spread in the results is surprisingly large, it is gratifying that a problem has been identified and can now be corrected. In spite of the fact that power was lost, the two Solid State Reference Standards performed extremely well, and have demonstrated that they provide a means by which 10 Volt standards at widely separated locations can be reconciled to within something like 0.1 ppm. We have also begun to gather information on the relative quality of various methods for measuring 10 Volts to the accuracies required to support the 5440A Direct Volts Calibrator. It is not surprising that the methods which compare the 10 Volt output of the 735C's to four or nine series connected cells yield greater precision than comparison to a single cell. The effects of thermal EMF's, the contribution of the divider to the measurement, and the instability of a particular cell all decrease in importance as the number of cells increases. We also should not overlook the fact that Fluke obtained very good results by comparing the test units to a working standard 735C at the 10 Volt level. This leads us inevitably to consider the possibility of maintaining the standard of voltage at the 10 Volt level.

Acknowledgements

The success of a project such as this depends upon the cooperation of many people. In this case, all involved did what had to be done competently and expeditiously. We take this opportunity to thank each of many people for their contribution to the success of this experiment. We particularly thank those we had personal contact with for their part in this project. We know that there were many others involved with which we had no contact, both higher and lower in the chain of command, at all the facilities. We would like to ask each of you to extend our appreciation to these on our behalf.

We also would like to thank the members of the Fluke Sales Force who so ably moved the 735C's into the out of the participating labs. In each case, it was their effort which made it possible to move the package between facilities in the short time span required. We especially thank Jay Fiske and Reed Buell at San Diego, Julius Gargyi at the Burbank office, and Warren Hagemeier of the Santa Clara office for taking the time from their busy schedules to make the experiment the success that it was.

FIGURE 1

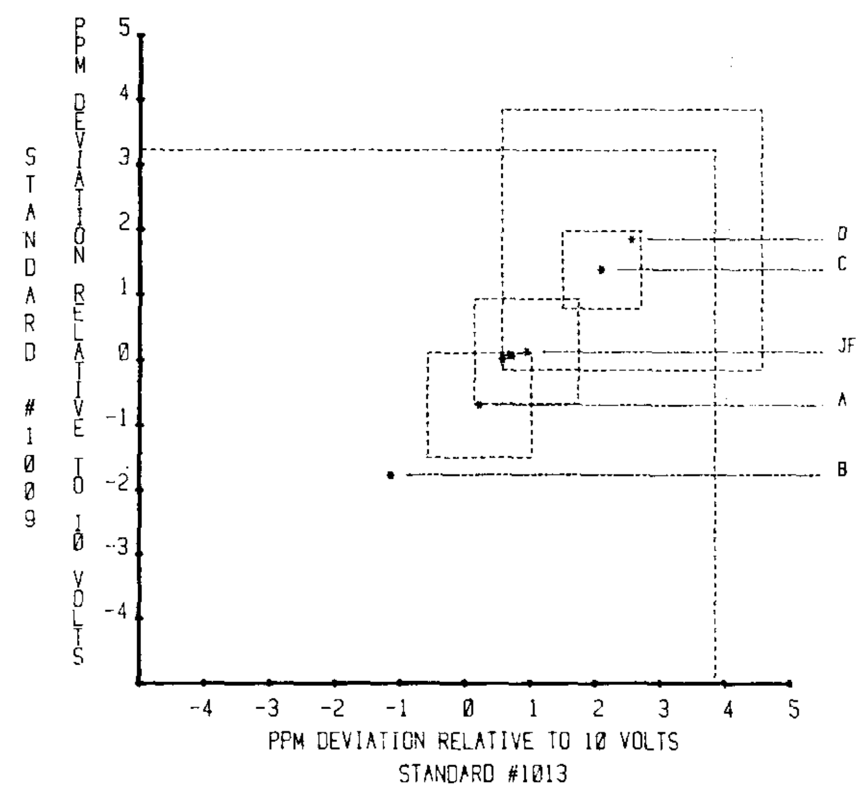


FIGURE 2

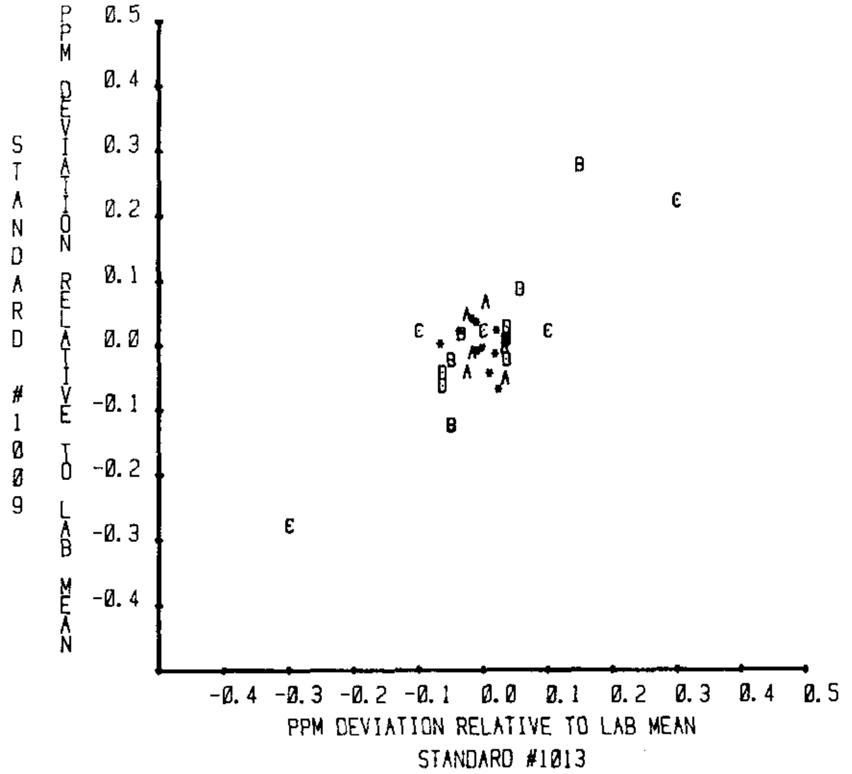
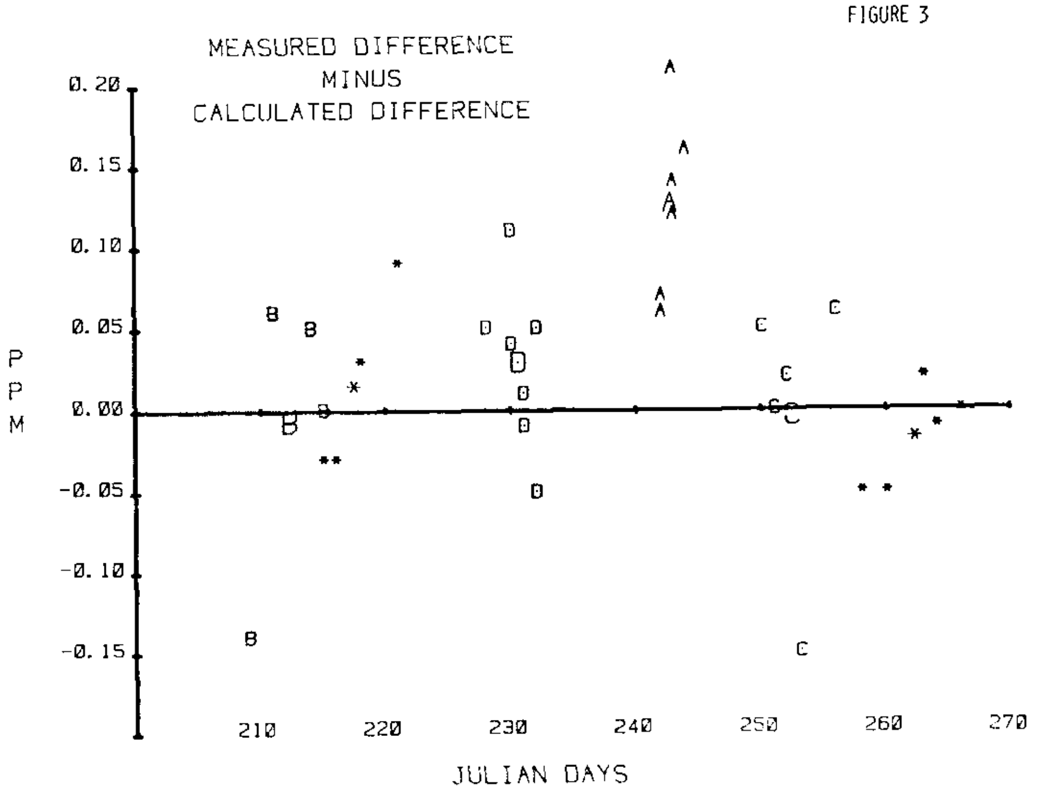


FIGURE 3



A FULLY AUTOMATIC SYSTEM FOR AC/DC DIFFERENCE CALIBRATION

K. J. Lentner, D. R. Flach
Electrosystems Division
National Bureau of Standards
Washington, D.C. 20234

Abstract

An automatic ac/dc difference calibration system using direct measurement of thermocouple emfs is described. The system operates over a frequency range of 0.02 to 100 kHz, and a voltage range of 0.5 to 1000 V. Analysis of the estimated systematic uncertainties and experimental data indicates that the ac/dc differences of single-range, coaxial-type thermal voltage converters (TVCs) were determined with total uncertainties in the range of 20 to 35 ppm (depending on frequency). Of these uncertainties, about 12 to 20 ppm represents the three standard deviation bounds for the effects of random errors, and the remainder the root sum of squares of bounds to possible systematic effects.

Summary

Until recently, most ac/dc difference tests were made using manual test systems which utilize photocell amplifiers and light beam galvanometers as voltage detectors. In addition, some test techniques required manual balance adjustments of a thermoelement (TE) comparator. Careful attention to the elimination or reduction of the effects of systematic and random uncertainty sources in testing methods has resulted in sufficient confidence in test data to allow results to be reported nominally with total uncertainties at the 10 to 100 ppm level (or better, in special cases) over wide voltage and frequency ranges. Manual test methods, however, are very time consuming and subject to errors due to operator fatigue and lack of skill. More recent work with semiautomatic systems and automatic balancing TE comparators overcame some of the deficiencies of manual test methods. However, these recently developed systems still require the use of TE voltage comparators which are not commercially available. In addition, the TE comparator adds to a system's cost and complexity.

To alleviate the tedium of making manual ac/dc difference measurements, to reduce the possibility of manual computational errors, to eliminate the sources of error due to operator fatigue and lack of skill, and to expedite test report generation, a desktop computer (DTC) controlled automatic test system (ATS) was developed. The system was designed to operate over a frequency range of 20 Hz to 100 kHz, covering the voltage range from 0.5 V to 1 kV, with expected ac/dc difference calibration uncertainties (including the uncertainty of the reference TVCs used) of 50 parts per million (ppm) for all voltages at frequencies in the range 20 Hz to 20 kHz, and 100 ppm for all voltages at frequencies in the range 20 kHz to 100 kHz. As stated in the abstract, test results using single-range, coaxial-type thermal voltage converters as transfer standards (between the ATS and the manually operated calibration system presently used at the National Bureau of Standards for routine calibration work) indicate that the data obtained with the ATS has uncertainties much lower than the design uncertainty limits. For the transfer standards used, the magnitude of the differences between the ac/dc differences obtained with the NBS manual system and the ATS ranged from zero to only 13 ppm. The specific standards used for the intercomparison tests included two with small ac/dc differences, and one with large but stable and accurately known ac/dc differences.

A block diagram of the system configuration is shown in the figure, and, as indicated, no TE comparator is used. Instead, the technique used is direct measurement of millivolt level dc voltages from the TEs. This technique has become feasible due to the availability of programmable and stable ac and dc voltage calibrators, and high resolution digital voltmeters (DVMs).

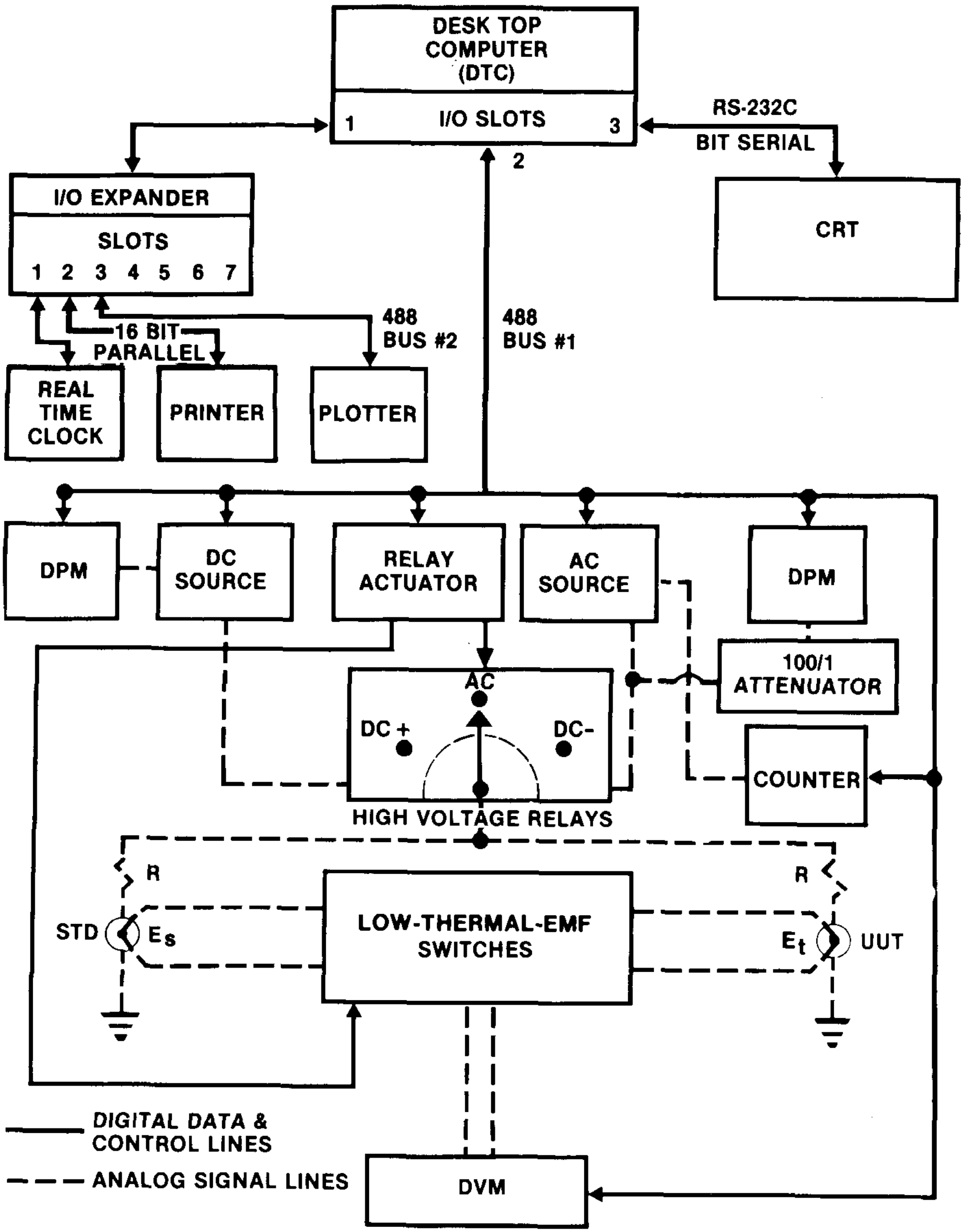
Control of the ATS is provided by the DTC which has about 60 kbytes of user-available memory with magnetic tape cartridges used for program and data storage. Communication from (and to) the DTC with the ATS measurement and stimulus equipment occurs via the IEEE-488 standard digital interface for programmable instrumentation.

The unit under test (UUT) is connected into the circuit as shown, and ac or dc voltages from the sources are automatically and simultaneously applied to the UUT and standard TVC. The UUT emf output is measured by the DVM, and compared against the measured emf of the standard TE. The computer controlled low-thermal-emf switches automatically select the TE emf output to be measured. The system clock precisely controls the time interval between application of the dc or ac voltages.

Determination of a TE's dimensionless characteristic "n" (a measure of its approach to a true square-law current response) is readily accomplished using the ATS. In addition, completely automatic tests of the ac and dc voltage source stabilities (with graphic plotting capability) can be made. DC reversal differences of a TE can be automatically determined, as well as the variations of reversal difference as a function of a TE's heater current. The TE's response time can also be measured, and the results automatically plotted, if desired.

Other important applications for the ATS are in calibrating ac calibrators and precision meters. Once calibration of the dc voltage source has been completed, this source, together with a standard TE and suitable range resistors, makes it possible to determine corrections to an ac voltage calibrator's nominal output voltage. Hence, the ATS's dc and ac voltage sources, each having known corrections stored in data files within the DTC's software, are available for calibrating DVMs and high precision analog meters.

In conclusion, the results indicate that it is feasible to make fully automatic precision ac/dc difference measurements. The principal advantage of the system is the elimination of any type of manually- or automatically-balanced TE comparator, permitting the system to be assembled using commercially available instrumentation, except for the switching modules. This approach, therefore, should make automation attractive to many calibration laboratories faced with the need to make ac/dc difference measurements. Moreover, the system can be used as a nearly-self-calibrating meter calibration system. Measurements can be done with minimal operator intervention, eliminating tedious and fatiguing manual operations. Hence, personnel presently engaged almost exclusively in manual ac/dc difference tests can be freed to do other work. Experience obtained during many years of testing with manually operated systems at NBS has shown that the precision of the test results is dependent upon operator skill. The automatic system's precision is independent of operator skill, eliminating this variable in the measurement uncertainty.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2
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CRT
I/O EXPANDER
SLOTS
1 2 3 4 5 6 7
16 BIT PARALLEL
488 BUS #2
488 BUS #1
REAL TIME CLOCK
PRINTER
PLOTTER
DPM
DC SOURCE
RELAY ACTUATOR
AC SOURCE
DPM
100/1 ATTENUATOR
AC
DC +
DC-
COUNTER
HIGH VOLTAGE RELAYS
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Et
UUT
DIGITAL DATA & CONTROL LINES
ANALOG SIGNAL LINES
DVM

IMPROVING DIVIDER CALIBRATION TECHNIQUES

Ross Endsley

Oak Ridge Y-12 Plant*
Union Carbide Corporation, Nuclear Division
Oak Ridge, Tennessee 37830

ABSTRACT

This paper describes the development of a procedure for calibration of precision voltage dividers. The procedure makes use of a reference divider made up of NBS-type resistors and a calibrated null detector. Although developed primarily for a seven-dial Kelvin-Varley divider with a span of 2111.111 units, it is adaptable to dividers with other spans. Typical results are presented along with a statistical discussion of repeatability. Advantages of the procedure are improved repeatability. increased confidence in corrections more rapid data acquisition, and independence from NBS for divider calibration.

BACKGROUND

While working for another company in 1968, the author was exposed to a method of calibrating a URS (Universal Ratio Set) by comparing each step of every dial to ten steps on the next lower dial. This may have been adequate for the accuracy required in the applications of that particular URS, but it left open the question of the effect of compensation errors. That is. when a step of any lower dial is added on the low end, another step is removed from the high end. If the steps removed are not exactly equal to the steps added, an error is introduced due to lack of "compensation."

In 1969, after joining the present company, the author computed the effect of this compensation error when comparing each step to ten steps on the next lower dial. At that time the company was calibrating two Universal Ratio Sets and an L&N 4399 Seven-Dial Kelvin-Varley Divider by moving an NBS type 100-ohm resistor through a string of similar resistors on mercury stands. This procedure is recommended by L&N (1) and does not suffer errors introduced by poor compensation. The degree of compensation (in the Universal Ratio Sets) was measured using Navy Procedure DR-03 (2). However, it was noticed that data from the moving resistor method at this lab was not very repeatable. In fact, it was sometimes difficult to tell from the data alone that two runs had been produced by the same instrument.

After several years of work in other areas. the author returned to electrical standards work in 1974. Since that time, considerable attention and interest have been devoted to divider calibration. There are two reasons for this emphasis. First, electrical measuring equipment generally available today is considerably more accurate than in the late sixties and places more demand on the higher level standards. Second, the National Bureau of Standards is attempting to limit their involvement in calibration work that can conceivably be done by industry personnel. Ratio calibrations are good examples of this trend.

The first attempt to deal with the repeatability problems was to construct a "perfect divider" that consisted of twenty-one 100-ohm resistors which could be individually adjusted so that all were equal. A regulated current was passed through the divider, and all the resistors were adjusted so that equal voltages appeared across each resistor. Stability of the regulated current and of the potentiometer used to measure the voltages was a source of trouble. Heating problems appeared at high currents, and thermal EMF problems appeared at low currents. In early 1979 the project was abandoned, and the L&N 4399 seven-dial divider was sent to NBS for calibration. When it returned, it was used to calibrate the two Universal Ratio Sets.

Since calibration by NBS would likely be discouraged in the future, another possible solution was explored. Section 7 of the old NBS Technical Note 220 by David Ramaley (3) was reviewed. The method described there is similar to that used by the author in 1968 for URS calibration comparing each step to ten steps on the next lower dial. However, seeing this note somehow suggested that the compensation error could be measured and calculated out. At the same time, if the seven-dial divider was used in place of the second URS, the resolution obtainable would be increased one order of magnitude. These accurately established corrections on the first dial of the URS could then be transferred back to the seven dial providing corrections for it.

* Operated for the U. S. Department of Energy by Union Carbide Corporation, Nuclear Division, under Contract W-7405-eng-26.

The method just described was attempted and almost succeeded. Equations were derived to correct for compensation error. The first few runs of data were inconsistent. Then it was realized that changes in contact resistance in the lower dials were causing the bad data. Using a new sequence of switching produced consistent data on everything except the magnitude of the compensation error. No practical switching sequence could be found to allow the same switch contact resistance to be present during the comparison of steps on the first dial as was present during the measurement of the compensation error. Because of this. the different runs produced data that had the same characteristic shape, but had larger differences between runs toward the center of the divider. It was calculated that an error of 4×10^{-4} divider units in the magnitude of the compensation error would cause an error of 10×10^{-4} divider units in a final correction near the center of the divider. Therefore, the experimentation with the URS ten-step substitution did not yield a satisfactory method. However, it did produce some beneficial results. First, it resulted in the application of a new instrument and technique. During the experimentation a new Keithley Model 181 Digital Nanovoltmeter became available. By using this new instrument in place of a conventional null detector, manipulation of the lower dials could be avoided and differences could be recorded in microvolts and later translated into divider units. The elimination of the tedious dial manipulation reduced the time required for data acquisition. It also meant that the lower dial switch contact resistance was no longer being changed in null seeking. The use of the nanovoltmeter did not cause loading errors because it has an extremely high input impedance (claimed to be greater than 1 G).

Another benefit realized was a partial explanation of the nonrepeatability experienced using the moving resistor method. Much of the nonrepeatability was no doubt caused by variations in switch contact resistance in the lower dials which were manipulated to achieve null at each setting. Because of its Kelvin-Varley construction. the main dial on the L&N 4399 should cause only half as much variation as the lower dial switches on the URS, assuming the same type switches are used. This effect in the lower dials of a Kelvin-Varley becomes less prominent by a factor of 2 for each lower dial. Since switch contact resistance is negligible in the presence of such high divider resistance, 100-kilohm Kelvin-Varley dividers apparently avoid these problems altogether.

A psychological benefit was realized from this work, also. As understanding increased and data became more repeatable, personnel confidence improved.

THE PRESENT METHOD

Early in 1982, it was decided to return to the use of NBS-type resistors. Every improvement in the method feasible for the lab was to be attempted. The NBS resistors were carefully compared and then used as a standard divider for calibration of the L&N 4399 Seven-Dial Divider. The same method with modifications has been successfully used in this lab on a 120-kilohm seven-dial Kelvin-Varley divider.

Fortunately. eleven 100-ohm NBS resistors were available along with mercury stands and a stable oil bath. To complete the divider, 1 kilohm. 10.01 ohm, 1 ohm, and 0.1 ohm resistors were used. Fourteen-gage copper wire was used to provide a voltage tap with mechanical rigidity at each mercury stand. Fourteen-gage copper was also used to tie in the 0.1-ohm resistor and make connections with the battery. The digital nanovoltmeter was connected from the galvanometer terminal to whichever voltage tap was desired on the standard divider. A schematic of the hookup is shown in Figure 1, and a photograph of the apparatus is shown in Figure 2.

Battery voltage was chosen to be 10.5 volts (obtained from seven 1.5-volt telephone dry cells in series). Most URS-type calibration procedures call for 4.5 volts, but 10.5 volts has certain advantages if the effect of additional heating can be tolerated. The use of 10.5 volts causes a power dissipation of only 2.5 milliwatts in each first dial resistor which would seem negligible. With a battery voltage of 10.5 volts, each 1×10^{-4} unit step on the seven-dial is almost exactly 0.5 microvolt. This makes the scale factor for translating the data from microvolts to 10^{-4} unit steps a simple multiplication by 2. This 0.5 microvolt/step also means that if untinned copper wire is used for hookup, thermal EMFs should amount to considerably less than one step. After some experimentation, the traditional reversing switch was omitted.

In taking data, each step on the first dial (e.g. step 200) was compared to the corresponding step on the standard divider. Then the ten steps of the second dial were added (e.g. step 2X0) and this was compared to the next step (300) on the standard divider. Upon reaching step 1000, the first 100 resistor and the 1-kilohm resistor were swapped, and the procedure could then be continued up to step 20X0. Sample data is shown in the first two columns of Tables I A & I B.

For the lower dials, a standard divider was formed from the same resistors used for the first dial except the 1-kilohm resistor was omitted. The battery voltage was reduced to 1.111 volts using a series decade box. This voltage was applied directly across the dial being calibrated using the terminals provided for this purpose by L&N. This arrangement provided a sensitivity of one microvolt per step (1×10^{-4} divider unit) for the second dial. For the third and fourth dials, the sensitivities were 10 and 100 microvolts per step, respectively. Sample data is shown for the second and third dials in the first two columns of Tables II and III.

For the last three dials of the divider, the accuracy requirements were reduced to the point that a direct check against the linearity of the Model 181 Nanovoltmeter was considered sufficient. The fourth dial again had 1.111 volts applied across it, and the nanovoltmeter was connected between the low end of the divider and the G terminal. The fourth dial was set to zero and the fifth dial to X. The applied voltage was readjusted until the nanovoltmeter read exactly 100 millivolts. Then the fifth dial was stepped down, and the nanovoltmeter was observed at each step. The sixth and seventh dials were checked in like manner with no change in the setup or applied voltage. In these checks, differences between the observed and nominal voltages of 10 microvolts would have indicated a correction of 0.1×10^{-4} divider units. No differences this great were observed.

In order to calibrate the standard divider, all eleven 100 Ω resistors were compared to a dummy resistor using the seven-dial as a one-to-one bridge. Additional resistance of 11.11 ohms was left in the high end of the circuit to make the seven-dial essentially direct reading. By using 2.11 volts across the seven-dial, corrections could be calculated directly from the microvolt readings, with no conversion necessary to divider units. Sample data from a comparison of the 100-ohm resistors is shown in the first four columns of Table IV.

The one remaining comparison necessary was the comparison of the 1-kilohm resistor to the first ten 100-ohm resistors. This was accomplished by using the seven dial as a one-to-one bridge again. The setup is exactly the same as that used for calibrating the first dial shown in Figure 1. The Rdg 1, 2, & 3 columns of Table V show sample microvolt readings and their conversion into divider units for this comparison. Four runs were averaged for this critical data.

CALCULATIONS

Calculations of the standard divider corrections were accomplished in the following manner. The corrections for the eleven 100-ohm resistors were calculated as shown in Table IV. The differences in readings across the dummy and the 100-ohm resistor being compared to the dummy were found and listed in the fifth and sixth columns as Δ_D and Δ_R, respectively. The seventh column is the difference between the two preceding columns and reflects the value of the eleven resistors compared to the dummy. These values include the error of the tenth step of the first dial of the seven-dial, but this is of no concern since the values were then adjusted to reference them to the sum of the first ten. This adjustment is shown in the next to the last column in Table IV. The last column is a summation of the corrections used in calculating corrections for the lower dials.

The calculation for the 1-kilohm resistor was similar, but here the seven-dial error was of concern. To properly account for this, the forward and reverse values were averaged. This is shown in Table V.

The corrections calculated in Tables IV and V for the eleven 100-ohm resistors and the 1-kilohm resistor were all referenced to the sum of the first ten 100-ohm resistors. These corrections were combined in order in the second column of Table VI A. In the third and fourth columns the reference was changed to the first 2000 ohms of the standard divider string. This allowed the correction at 2000 units to be zero. A summation of these individual resistor corrections was made in the fifth column to find the standard divider corrections at each point on the lower half of the seven-dial.

Table VI B uses the individual corrections from the fourth column of Table VI A, but rearranged in the correct order to calculate the standard divider corrections for the upper-half points on the seven-dial.

In calculating the corrections for the first dial, the first step was to convert the microvolt readings into divider units by multiplying by 2. This is shown in Column 3 of Tables I A and I B. A linear correction was applied in Columns 4 and 5 in order to make the corrections at zero and 2000 units equal to zero. The standard divider corrections from Tables VI A and VI B are shown in Column 6. The last column contains the final corrections which were calculated by subtracting the corrected ΔRs from the standard divider corrections.

Corrections for the second dial, shown in Table II, were calculated the same way as for the first dial except the readings did not have to be converted. The applied voltage was selected to make one microvolt equal to 1×10^{-4} divider unit. The standard divider corrections used here are those shown in the last column of Table IV, divided by 10.

For the third dial corrections, shown in Table III, the microvolt readings were divided by 10, and the standard divider corrections were those in the last column of Table IV, divided by 100. For the fourth dial, the readings were divided by 100 and the standard corrections by 1000. The table for the fourth dial was omitted because of its similarity to Table III. It should be clear that, if the 100-ohm resistors used are close enough to nominal, the standard divider corrections will be unnecessary for the third and fourth dials.

ANALYSIS OF RESULTS AND DISCUSSION

The method just described provided improved repeatability compared with the other methods previously attempted in this lab. Corrections from six runs by two persons over a period of about three months were averaged. The largest standard deviation observed for any point during these six runs was 1.7×10^{-4} divider units. The average standard deviation for all points was 0.75×10^{-4} units. These numbers constitute an order of magnitude improvement over the earlier attempts in this laboratory. They also should be useful indicators of what can be expected from similar work in other labs.

The differences that were observed during the six runs were probably due to the following causes. The variations in mercury stand contact resistance were investigated and found to cause variations of as much as 2.4×10^{-4} divider unit. However, the typical variation was 1.4×10^{-4} divider unit or less. The mercury stand contact resistance could be virtually eliminated as a source of error if higher resistance standard divider resistors were used. Variations caused by switch contact resistance were also investigated and appeared to make a somewhat smaller contribution, typically less than 1.0×10^{-4} divider unit, with a maximum of 1.4×10^{-4} divider unit. This was after exercising the switches as many people advise. Variations in the true corrections of the seven-dial could have contributed to the differences, but over such a short period of time it is suspected that these changes would not likely be significant.

In looking back at the moving resistor method of calibration, some thoughts are offered. This early work was accomplished using resistors and mercury stands located on an open bench-top where they were exposed to air currents and changing temperature gradients. No doubt the repeatability for the moving resistor method would be much improved if it were performed in a regulated oil bath as in the method presented here. It has been observed that other labs using a fixed standard divider are able to achieve excellent results using resistors in an insulated lag chamber. with or without oil immersion.

Looking back even further, URS calibration, by comparing each step to ten steps on the next lower dial, suffers the seemingly fatal problem of compensation error. The nature of the URS works against attempts to measure and correct for compensation error. On a new instrument, contact resistance variations may not present so great an obstacle. The question of URS calibration has lost some of its importance today, as even some lab-type potentiometers are being replaced by digital multimeters and Universal Ratio Sets by Kelvin-Varley dividers.

Obviously, the method presented here can be applied to Kelvin-Varley dividers having a full scale of 1.0, 1.1, or 1.2. In fact, it is even simpler than for the L&N Model 4399 if the required number of nominally equal resistors are available.

CONCLUSIONS

Advantages realized in the Y-12 Physical and Electrical Standards Laboratory from the method of divider calibration presented here are:

1. An order of magnitude improvement in repeatability of corrections.
2. Increased confidence in the corrections as a result of statistical analysis.
3. More rapid data acquisition, primarily because of the use of a calibrated digital null detector.
4. Independence from NBS in this area of ratio calibration.

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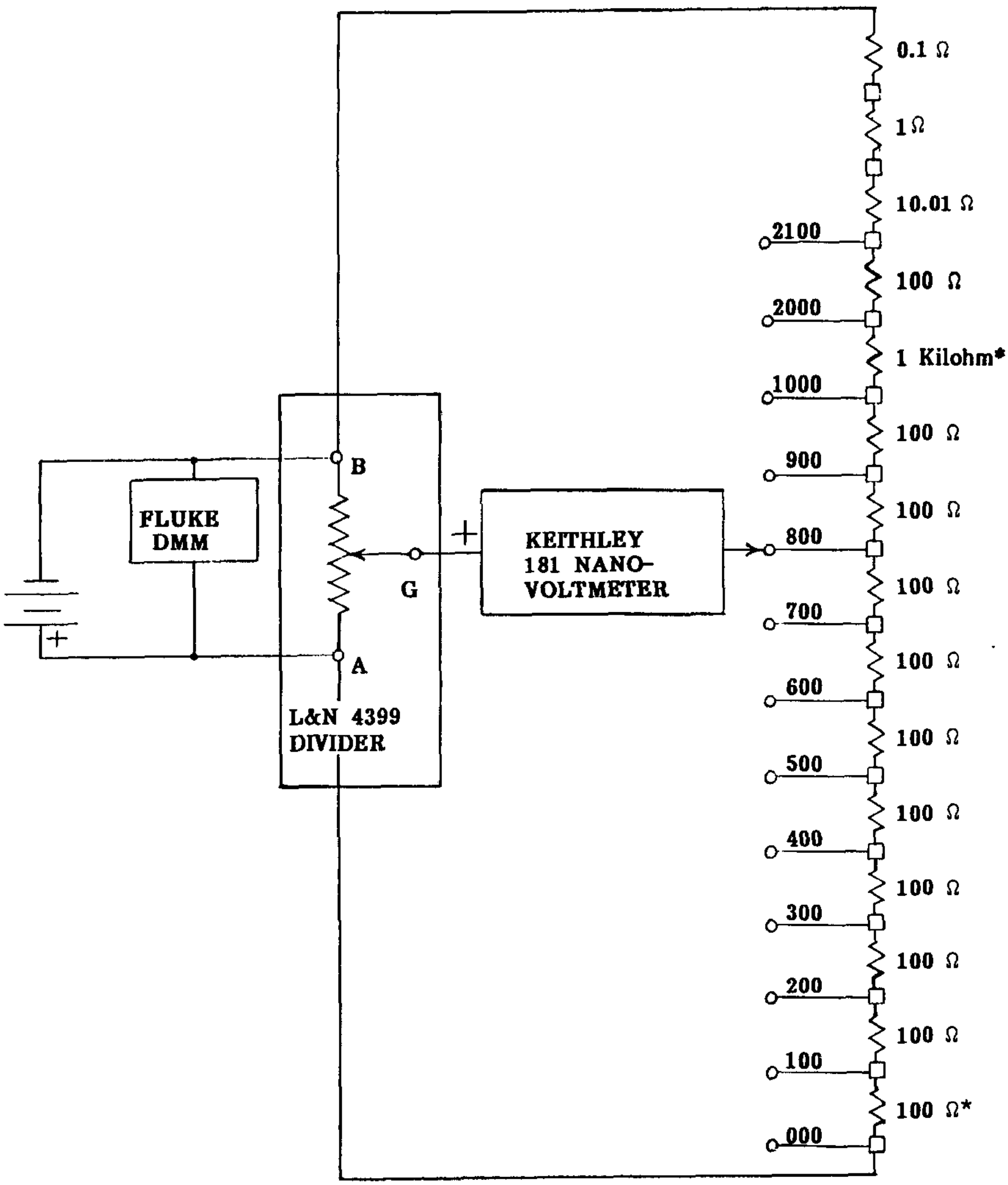

*These two resistors are interchanged to obtain points ranging from 1000 to 2100 divider units.

FIGURE 1 - FIRST DIAL CALIBRATION

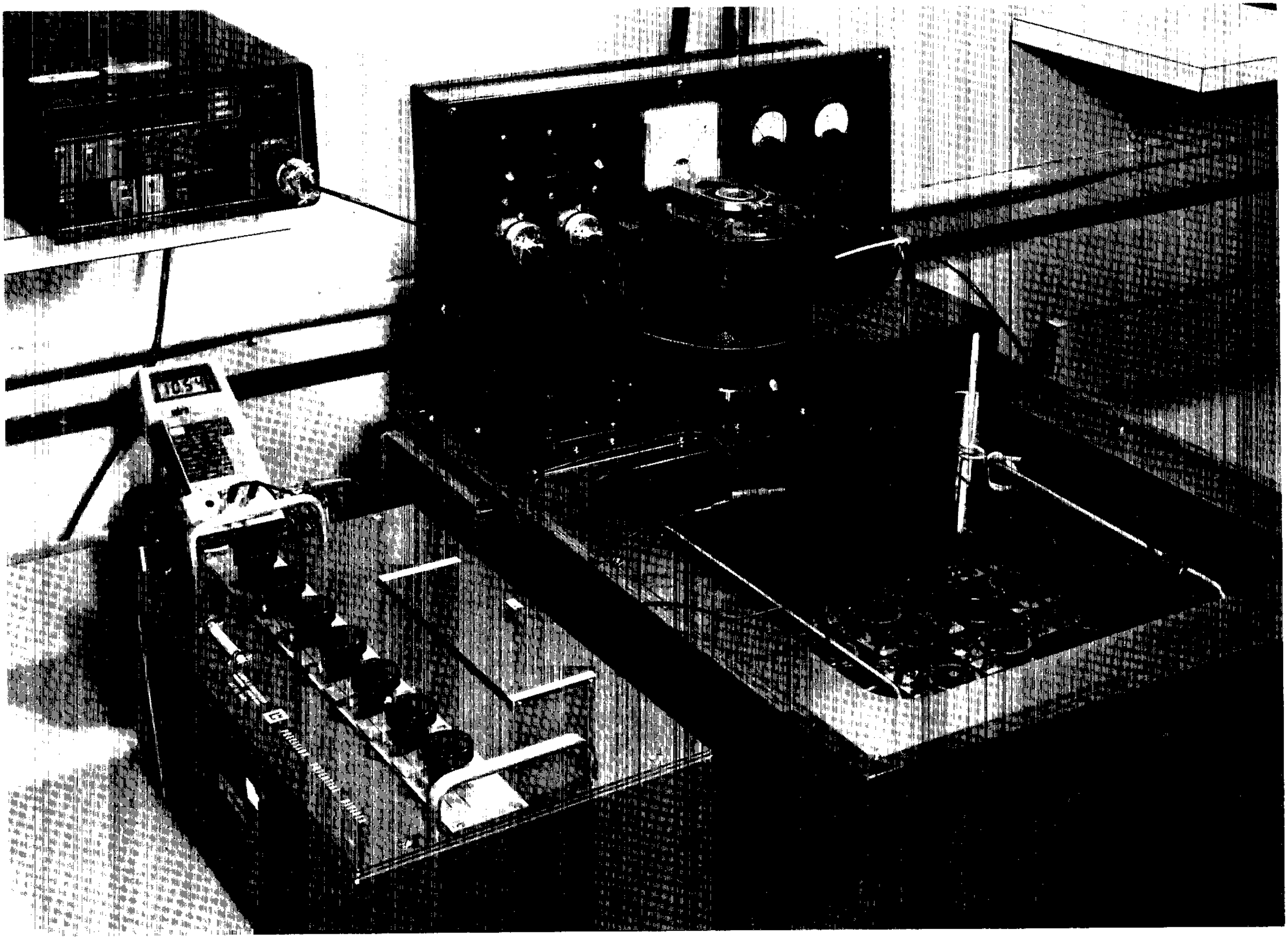

FIGURE 2 - DIVIDER CALIBRATION APPARATUS

TABLE I A

Data and Calculation of Corrections
Lower Half of First Dial

Seven Dial Setting	181 Reading ΔV (μV)	ΔR = 2 ΔV (Units x 10^4)	Linear Correction	Corrected ΔR	Standard Divider Correction	Seven Dial Correction C_1 x 10^4
1000	-0.5	-1.0				
2000	1.6	3.2	-3.2	0		
000	5.7	11.4	-11.4	0	0	0
0X0	-8.8	-17.6	-11.0	-28.6	-33.9	-5.3
100	-10.8	-21.6	-11.0	-32.6	-33.9	-1.3
1X0	-5.8	-11.6	-10.6	-22.2	-28.7	-6.5
200	-6.0	-12.0	-10.6	-22.6	-28.7	-6.1
2X0	-4.0	-8.0	-10.2	-18.2	-27.9	-9.7
300	-5.3	-10.6	-10.2	-20.8	-27.9	-7.1
3X0	-2.9	-5.8	-9.8	-15.6	-26.7	-11.1
400	-2.8	-5.6	-9.8	-15.4	-26.7	-11.3
4X0	4.5	9.0	-9.4	-0.4	-17.2	-16.8
500	2.4	4.8	-9.4	-4.6	-17.2	-12.6
5X0	5.2	10.4	-8.9	1.5	-12.7	-14.2
600	6.0	12.0	-8.9	3.1	-12.7	-15.8
6X0	5.5	11.0	-8.5	2.5	-14.0	-16.5
700	3.3	6.6	-8.5	-1.9	-14.0	-12.1
7X0	3.0	6.0	-8.1	-2.1	-16.9	-14.8
800	-0.1	-0.2	-8.1	-8.3	-16.9	-8.6
8X0	1.5	3.0	-7.7	-4.7	-18.0	-13.3
900	0	0	-7.7	-7.7	-18.0	-10.3
9X0	2.3	4.6	-7.3	-2.7	-18.7	-16.0
1000	-0.5	-1.0	-7.3	-8.3	-18.7	-10.4
000	5.3	10.6				

TABLE I B

Data and Calculation of Corrections
Upper Half of First Dial

Seven Dial Setting	181 Reading ΔV (μV)	ΔR = 2 ΔV (Units x 10^4)	Linear Correction	Corrected ΔR	Standard Divider Correction	Seven Dial Correction C_1 x 10^4
000	5.4	10.8	-10.8	0		
2000	1.9	3.8				
1000	18.0	36.0	-6.9	29.1	18.7	-10.4
10X0	21.7	43.4	-6.5	36.9	23.8	-13.1
1100	21.8	43.6	-6.5	37.1	23.8	-13.3
11X0	21.7	43.4	-6.1	37.3	24.7	-12.6
1200	18.0	36.0	-6.1	29.9	24.7	-5.2
12X0	18.0	36.0	-5.7	30.3	25.9	-4.4
1300	17.1	34.2	-5.7	28.5	25.9	-2.6
13X0	21.4	42.8	-5.3	37.5	35.4	-2.1
1400	18.7	37.4	-5.3	32.1	35.4	3.3
14X0	20.7	41.4	-5.0	36.4	39.8	3.4
1500	18.0	36.0	-5.0	31.0	39.8	8.8
15X0	16.8	33.6	-4.6	29.0	38.6	9.6
1600	17.3	34.6	-4.6	30.0	38.6	8.6
16X0	16.3	32.6	-4.2	28.4	35.7	7.3
1700	16.0	32.0	-4.2	27.8	35.7	7.9
17X0	18.2	36.4	-3.8	32.6	34.5	1.9
1800	14.9	29.8	-3.8	26.0	34.5	8.5
18X0	15.9	31.8	-3.4	28.4	33.9	5.5
1900	16.7	33.4	-3.4	30.0	33.9	3.9
19X0	1.4	2.8	-3.0	-0.2	0	0.2
2000	1.5	3.0	-3.0	0	0	0
20X0	5.4	10.8	-2.6	8.2	2.4	-5.8
1000	18.2	36.4				

TABLE II

Data and Calculation of Corrections
Second Dial

Seven Dial Setting	181 Reading ΔV (μV) or ΔR(Units x 10^4)	Linear Correction	Corrected ΔR	Standard Divider Correction	Seven Dial Corrections $C_2 \times 10^4$
000	-121.1				
0X0	81.8				
000	-121.2	121.2	0	0	0
00X	-103.6	100.8	-2.8	-3.2	-0.4
010	-104.2	100.8	-3.4	-3.2	0.2
01X	-82.4	80.5	-1.9	-2.5	-0.6
020	-82.8	80.5	-2.3	-2.5	-0.2
02X	-61.9	60.2	-1.7	-2.2	-0.5
030	-62.4	60.2	-2.2	-2.2	0
03X	-41.0	39.8	-1.2	-1.9	-0.7
040	-41.9	39.8	-2.1	-1.9	0.2
04X	-19.7	19.4	-0.3	-0.8	-0.5
050	-19.9	19.4	-0.5	-0.8	-0.3
05X	1.4	-0.9	0.5	-0.2	-0.7
060	0.7	-0.9	-0.2	-0.2	0
06X	21.6	-21.2	0.4	-0.1	-0.5
070	21.0	-21.2	-0.2	-0.1	0.1
07X	41.5	-41.6	-0.1	-0.2	-0.1
080	41.2	-41.6	-0.4	-0.2	0.2
08X	62.4	-62.0	0.4	-0.1	-0.5
090	61.3	-62.0	-0.7	-0.1	0.6
09X	81.9	-82.3	-0.4	0	0.4
0X0	82.3	-82.3	0	0	0
0XX	103.5	-102.6	0.9	0.4	-0.5
000	-121.7				

TABLE III

Data and Calculation of Corrections
Third Dial

Seven Dial Setting	181 Reading ΔV (μV)	ΔR (Units x 10^4)	Linear Correction	Corrected ΔR	Standard Divider Correction	Seven Dial Corrections C_3 x 10^4
0.0	-267.9	-26.8				
X.0	200.6	20.1				
0.0	-268.7	-26.9	26.9	0	0	0
0.X	-224.2	-22.4	22.2	-0.2	-0.3	-0.1
1.0	-223.7	-22.4	22.2	-0.2	-0.3	-0.1
1.X	-175.7	-17.6	17.5	-0.1	-0.2	-0.1
2.0	-175.5	-17.6	17.5	-0.1	-0.2	-0.1
2.X	-128.0	-12.8	12.8	0	-0.2	-0.2
3.0	-128.0	-12.8	12.8	0	-0.2	-0.2
3.X	-80.7	-8.1	8.1	0	-0.2	-0.2
4.0	-81.0	-8.1	8.1	0	-0.2	-0.2
4.X	-33.0	-3.3	3.4	0.1	-0.1	-0.2
5.0	-33.0	-3.3	3.4	0.1	-0.1	-0.2
5.X	14.3	1.4	-1.3	0.1	0	-0.1
6.0	13.7	1.4	-1.3	0.1	0	-0.1
6.X	60.9	6.1	-6.0	0.1	0	-0.1
7.0	60.8	6.1	-6.0	0.1	0	-0.1
7.X	107.7	10.8	-10.7	0.1	0	-0.1
8.0	107.2	10.7	-10.7	0	0	0
8.X	154.4	15.4	-15.4	0	0	0
9.0	153.8	15.4	-15.4	0	0	0
9.X	200.1	20.0	-20.0	0	0	0
X.0	200.4	20.0	-20.0	0	0	0
X.X	247.0	24.7	-24.7	0	0	0
0.0	268.3	26.8				

TABLE IV - Comparison of 100Ω Resistors

SN of Compared Resistor	181 Readings ΔV(μV) Seven Dial at 000 Rdg 1	Seven Dial at 1000 Rdg 2	Seven Dial at 2000 Rdg 3	Δ_D Difference Across Dummy 100Ω Resistor, Rdg 2 - Rdg 1	Δ_R Difference Across Compared 100Ω Resistor, Rdg 3 - Rdg 2	C_D Corrections for Resistors Ref Dummy $\Delta_R - \Delta_D$ (Units x 10^4)*	C_{10} Corrections for Resistors Ref First Ten, C_D - Σ/10 (Units x 10^4)	ΣC_{10} Corrections for Each Step for 10 Step Dials (Units x 10^4)
1807	52.3	4.6	-78.0	-47.7	-82.6	-34.9	-32.0	-32.0
4249	52.2	-13.1	-74.3	-65.3	-61.2	4.1	7.0	-25.0
4242	52.1	-10.6	-73.5	-62.7	-62.9	-0.2	2.7	-22.3
4230	52.0	-11.0	-73.8	-63.0	-62.8	0.2	3.1	-19.2
7247	52.0	-15.3	-74.1	-67.3	-58.8	8.5	11.4	-7.8
4227	52.1	-12.3	-73.3	-64.4	-61.0	3.4	6.3	-1.5
4232	52.1	-10.5	-75.4	-62.6	-64.9	-2.3	0.6	-0.9
4226	52.2	-9.0	-74.1	-61.2	-65.1	-3.9	-1.0	-1.9
4235	52.1	-10.6	-75.5	-62.7	-64.9	-2.2	0.7	-1.2
4246	52.3	-11.2	-76.4	-63.5	-65.2	-1.7	1.2	0
						Σ = -29.0	0.0	
4245	52.2	-11.9	-74.6	-64.1	-62.7	1.4	4.3	

*Using 2.11 volts across the Seven Dial, one microvolt on the Model 181 detector is equal to 100 microhms. When the resistors are placed in the 2111.111 ohm standard divider string, 100 microhms is equivalent to 1 x 10^{-4} divider units.

TABLE V - Comparison at 1000 OHMS

	Seven Dial at 000 Rdg 1	Seven Dial at 1000 Rdg 2	Seven Dial at 2000 Rdg 3	Δ_Σ Difference Across Sum of 10 x 100Ω	Δ_K Difference Across 1K Resistor	C_{10} Correction for 1K Ref Sum of 10 x 100Ω $\Delta_K - \Delta_\Sigma$
Forward Readings				Rdg 2-Rdg 1	Rdg 3-Rdg 2	
181 Readings ΔV(μV)	5.3	-0.8	0.3			
ΔR = 2 ΔV (Units x 10^4)	10.6	-1.6	0.6	-12.2	2.2	14.4
Reverse Readings				Rdg 3-Rdg 2	Rdg 2-Rdg 1	
181 Readings ΔV(μV)	5.4	17.8	0.0			
ΔR = 2 ΔV (Units x 10^4)	10.8	35.6	0.0	-35.6	24.8	60.4
					Avg =	37.4

TABLE VI A

Standard Divider Corrections
Lower Half Corrections

SN of Resistor	C_{10} Correction Ref Sum of 10 x 100Ω (Units x 10^4)	p Proportional Correction, Σ/20 or Σ/2	C Correction Ref 2000Ω String, $C_{10} - p$	ΣC Lower Half Standard Divider Correction (Units x 10^4)	Corresponding Tap on Divider (Units)
1807	-32.0	1.87	-33.87	-33.9	100
4249	7.0	1.87	5.13	-28.7	200
4242	2.7	1.87	0.83	-27.9	300
4230	3.1	1.87	1.23	-26.7	400
7247	11.4	1.87	9.53	-17.2	500
4227	6.3	1.87	4.43	-12.7	600
4232	0.6	1.87	-1.27	-14.0	700
4226	-1.0	1.87	-2.87	-16.9	800
4235	0.7	1.87	-1.17	-18.0	900
4246	1.2	1.87	-0.67	-18.7	1000
1K	37.4	18.70	18.70	0	2000
	Σ = 37.4		0.00		
4245	4.3	1.87	2.43	2.4	2100

TABLE VI B

Standard Divider Corrections
Upper Half Corrections

SN of Resistor	C Correction Ref 2000Ω String, $C_{10} - p$	ΣC Upper Half Standard Divider Correction (Units x 10^4)	Corresponding Tap on Divider (Units)
1K	18.70	18.7	1000
4249	5.13	23.8	1100
4242	0.83	24.7	1200
4230	1.23	25.9	1300
7247	9.53	35.4	1400
4227	4.43	39.8	1500
4232	-1.27	38.6	1600
4226	-2.87	35.7	1700
4235	-1.17	34.5	1800
4246	-0.67	33.9	1900
1807	-33.87	0	2000
4245	2.43	2.4	2100

IMPROVING DIVIDER CALIBRATION TECHNIQUES

Ross Endsley

Oak Ridge Y-12 Plant
Operated by Union Carbide Corporation
for the United States Department of Energy

Abstract

Automated test equipment presents many problems to the user. As time goes on, the value of the system may increase because of increasing costs of replacement and increasing dependence on the system. One approach to the problem of older ATE is to increase it's maintainability by using more recent technology to overcome specific problems of the test station. The Navy used this method to decrease the downtime encountered when the microwave portion of a test set had to be maintained and calibrated. The details of this method are described and the benefits are summarized.

INTRODUCTION

There are a number of early generation Automated Test Equipment systems, ATE, in use by the military. These systems pose many unique problems to the users. One problem is maintainability. The older systems present problems with parts, increasing maintenance and decreasing reliability. Although a system is old, its value will increase with time. A system's value will increase because the value reflects the cost of replacement, and the cost of not doing the job. An old ATE system may be hard to live with, impossible to live without and expensive to replace.

The Navy's Mini-Sace is an early generation ATE system used to support the A6 aircraft. The Mini-Sace consists of three separate punched tape controlled consoles: radar, air data simulator, and control function. There is a Mini-Sace system on each of the fourteen "Big Deck" carriers, and approximately twenty shore based stations. The microwave drawer of the radar test station poses special problems to the Navy. This drawer contains the main stimulus and response circuits and requires calibration. Calibration of the microwave drawer required several days of downtime if done on-line. The radar console has a heavy workload and can only test a few functions without the microwave drawer. Downtime to calibrate the microwave drawer is doubly painful. The only alternative to on-line calibration is disassembling all the mircowave components, calibrating each one individually, and then reassembling the drawer. This component approach would not guarantee the functioning of the microwave drawer once it was reassembled.

The solution chosen by the Navy was to treat the drawer as though it were a system, and develop an off-line controller for it. An instrument controller and an interface box controlled over the IEEE-488 bus are the major components of the off-line controller. The interface box would provide the electrical interface to the microwave drawer, and would not contain any of the sequential control required to run the drawer. The control functions would be handled by the controller over the IEEE-488 bus. This approach proved successful.

The first phase of the project was to determine the interface requirements of the microwave drawer by studying the documentation. The information obtained was checked out using a hardwired breadboard. The breadboard consisted of switches and pushbuttons, and was intended only to proof the electrical requirements of the drawer. The updated requirements were used to write the specification to procure the interface box. A desk-top computer was used to control the interface box. The sequencing needed to activate the microwave switches, select frequencies, and set attenuator values was determined using this combination. Once the sequencing was understood, the software for the Navy's instrument controller and the calibration procedure were written.

System Requirements

The Mini-Sace microwave drawer is controlled by relays and TTL logic. The relays are activated by voltage sources and sinks in a matrix arrangement applied through the main connector. A particular relay would be selected by the combination of a voltage source and a sink. In addition to the 28 Vdc relay drivers, there were a number of 28 Vdc receivers. These monitor the responses and the condition of the Mini-Sace microwave drawer. Part of the sequence to control a relay requires an "OK to go" signal to be received. There are a number of other 28Vdc signals that monitor the settings of microwave switches, attenuators and other functions. There are also TTL receivers and drivers. The drivers control the motorized attenuator setting. The receivers read the power meter and the setting of the attenuator. The TTL drivers and receivers are also used in continuity checks of the safety interlocks. To add to the confusion, there is also a servo interface. The servo is used to set the output level of a microwave source after a new frequency is selected. The only way to be sure the output is leveled is to watch what the servo is doing. Once the servo is zeroed, the level is set and the test can proceed. The interlocks make sure the one kilowatt dummy load is operated safely. The test points connect to the analog output of the power meter, the servo leveling loop and several other important analog signals. Two interface cables are required. One is the 156 pin main interface, containing all the signals described above. The other is a 30 pin connector for the power supplies. Figure 1 is a picture of the microwave drawer. The main interface connector is to the right. The other rectangular connector is the power supply connector. The fan for the dummy load is located on the left. Some of the waveguide switches and the attenuator are visible.

One assumption made was it is easier to change software than hardware. The software intensive approach allowed changes in operation to be made in the controller's software and not the firmware in the interface box. The interface box was built by a contractor for the Navy. By using an interface, the Navy accepted the responsibility for the overall operation of the system. This approach was dictated because there were no spare Mini-Sace microwave drawers to be loaned for the time required.

Future uses of the off-line controller had to be considered. To keep the unit flexible, the idea of a personality module similar to the ones used in prom programmers was adopted. By changing the personality module and the software, the air data simulator drawer or another system could be interfaced.

There were a number of restrictions on the development of the off-line controller. The microwave drawers were in short supply. In fact there was one less than there were Mini-Sace stations. When one carrier came into port the microwave drawer was taken off and installed on a outbound carrier. The shore based Mini-Sace systems were not readily available. The workloads on the system did not permit the downtime necessary to develop the off-line controller. During the early phases of the project the documentation for the Mini-Sace system was studied. All the manuals available were stamped "PRELIMINARY". No manual is perfect, but there were a number of gray areas that seemed black at the time. One further problem was the lack of people. The tasks had to be selected, so those tasks that could be done only by the Navy were done by the Navy. The design of the interface system was influenced as much by these non-hardware requirements as by the hardware requirements.

The Approaches

The off-line controller for the microwave drawer has four distinct parts. The first, as shown in figure 2, consists of the voltage drivers and receivers that provide the electrical interface to the drawer. The second part is the sequencing necessary to energize a relay in the microwave drawer. The correct sequence of steps necessary to perform a task is the next part of the system. Setting the value of the attenuator, or changing frequencies of the oscillator are such tasks. The final part of the system is the set of tasks, or procedure, required to calibrate or perform maintenance on the drawer. Three of the four parts of the system are really software, and make up the intelligence of the system.

One major decision made in the design

of the microwave drawer controller was how to partition the system. One approach would have been to lump everything into one box. The results would have been a larger, more expensive box that only did one thing. Much of this design would have been "reinventing the wheel" because most of the processing could be handled by a desktop computer or instrument controller. Another approach would be to combine the sequencing with the drivers and the procedure with the tasks. The exact sequencing was not known until much later in the project. This approach would have required software in two units to be changed frequently. One approach seriously considered was to include the drivers, the sequencing and the tasks in one unit and feed in procedures from another. This would require one unit to have most of the capability, and the second to act like a tape deck. This approach was not used because it lacked flexibility.

Results

The partitioning chosen was to include all the processing in one box and the electrical interface in another. The electrical interface would be controlled over the IEEE-488 bus so the unit would have to have some processing capability. The job of converting a procedure into a series of instructions to operate the drivers is well within the capabilities of an off-the-shelf instrument controller. One other benefit of this arrangement was evident during the development stage. The exact operation of the drawer had to be determined during development of the off-line controller. True, relay drivers were required, but some questions about timing could not be answered from the documentation, and a full system was not available. The use of the instrument controller allowed a sequence to be tried and revised immediately. Even a system using a compiler instead of an interpreter would have been unsatisfactory because of the extra time involved.

The original control software was written using a building block approach on a Hewlett Packard 9830. A microwave drawer was obtained and the software written to discover how the drawer worked. As tests of each function were completed, the control software was revised. The basic interpreter allowed quick software revisions. The questionable documentation and the complex nature made this building block approach necessary.

The first version of the control software was considered completed when the maintenance program for the drawer was functioning. This program exercised every relay, microwave switch and setting in the drawer. A failure during this program would be noted and the offending item replaced. This maintenance program demonstrated all the functions of the drawer were controllable, and the operation of the drawer was understood. The calibration procedure was then written. Since the drawer was treated as a system, entire rf paths could be tested. The calibration of the microwave drawer can be completed in one day.

Figure 3 is a block diagram of the electrical interface to the microwave drawer. The electrical interface box consists of a mainframe and a removable personality module. The personality module consists of an interface module and connectors. The processor module of the mainframe talks to the instrument controller and translates its commands into the correct actions. The interface module contains the drivers and receivers that form the electrical interface to the microwave drawer. One requirement for the interface is for everything to be off when the unit first comes up. The power relays are used to make sure the power routed through the interface is controlled. There are a number of spare circuits to allow for a change in the microwave drawer or a slightly different application.

The first level of software is illustrated in figure 4. This is the basic sequence to turn on a source and a sink to activate a relay. When the "OK-to-go" signal is received the relay is in its new position and the source and sink are turned off. Figure 5 shows the sequence of commands necessary to perform a task, in this case to set the motorized attenuator.

The drawer is first addressed. The TTL drivers are set for the desired value, and the attenuator enabled by setting several relays. There is a 28Vdc receiver monitoring the motor of the attenuator. When the motor stops the attenuator is disabled and its value read. If the value is not correct, the process is repeated. If the value is correct the drawer is unaddressed and the task is complete. The calibration and maintenance procedures consist of lists of these command sequences. Also, the operator can control the microwave drawer without using a fixed procedure. This feature is important when troubleshooting because it allows the operator to repeat a sequence to locate a fault.

Conclusions

The partitioning of the off-line controller was a key element in the success of the project. The interface box only had to provide the correct signals and to respond to the commands of the instrument controller. This partitioning allowed the interface box to be built before operation of the drawer was fully understood and saved a considerable amount of time. Since the software was soft and not firm, the programs used to control the drawer could easily and quickly be developed. The use of the personality module allowed flexibility for other applications. Other drawers can be interfaced by changing the personality module and the software.The Mini-Sace punched tape controller could be replaced by using the same approach that worked for the microwave drawer. A new personality module and a change of software is all that is required. The partitioning broke the project down into reasonably sized and compatible tasks.

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[2] Operation and Maintenance Manual, Programmable Interface Unit Mainframe Model 1060, Arbiter Systems Inc, 1982.

[3] Operation and Maintenance Manual, Programmable Interface Unit For Mini-Sace Microwave Drawer Model 1060-200, Arbiter Systems Inc, 1982.

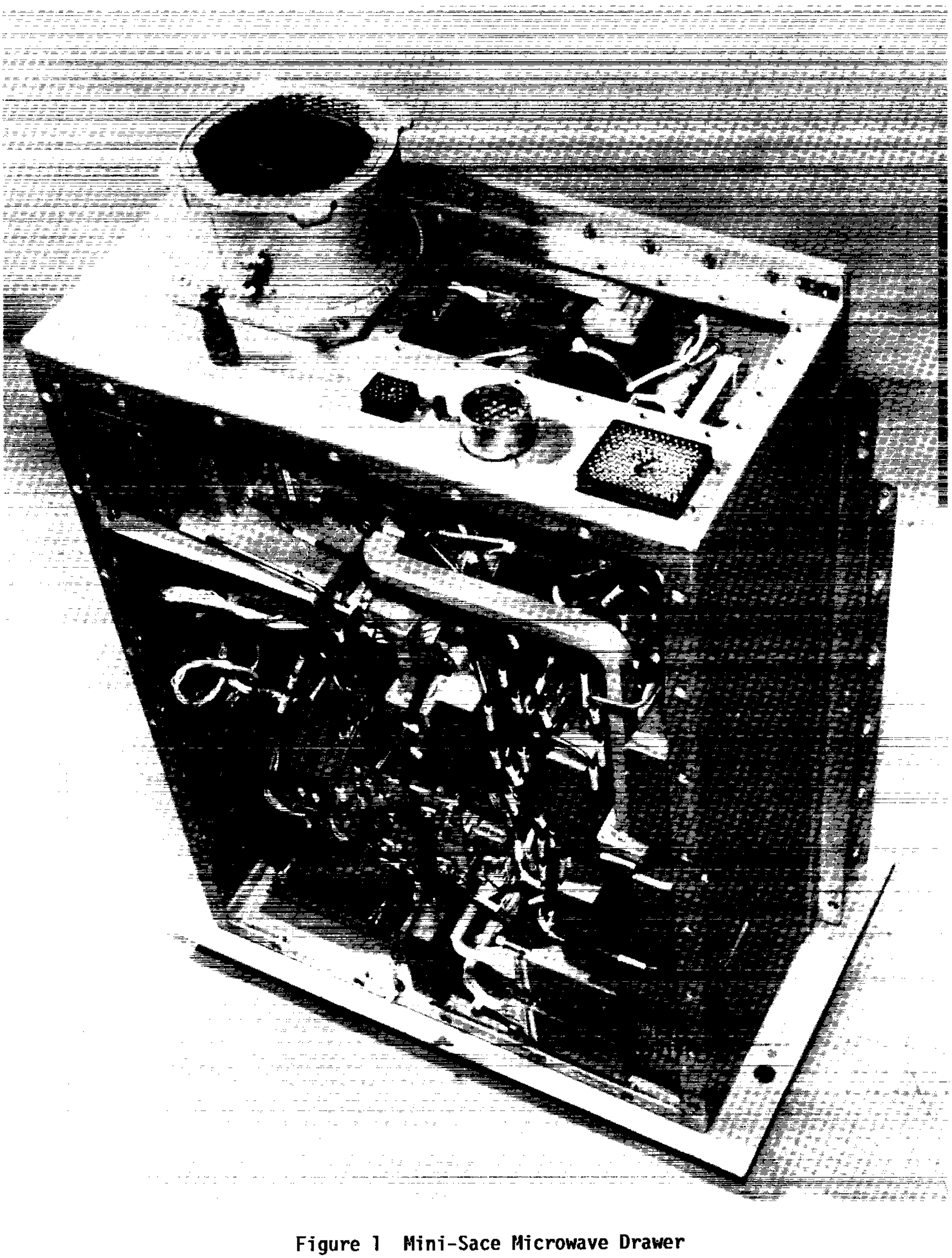

Figure 1 Mini-Sace Microwave Drawer

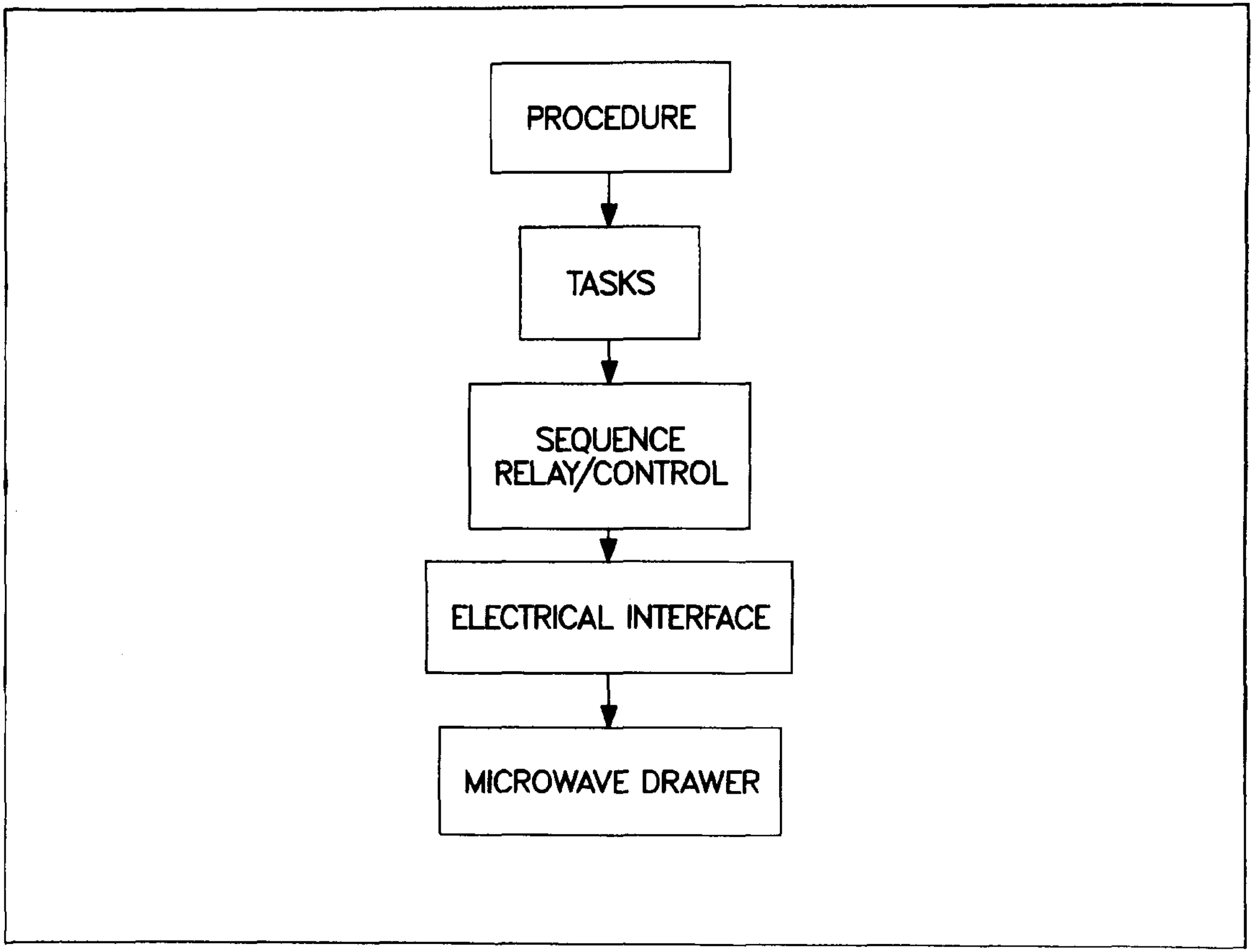

Figure 2 Off-Line Controller Block Diagram

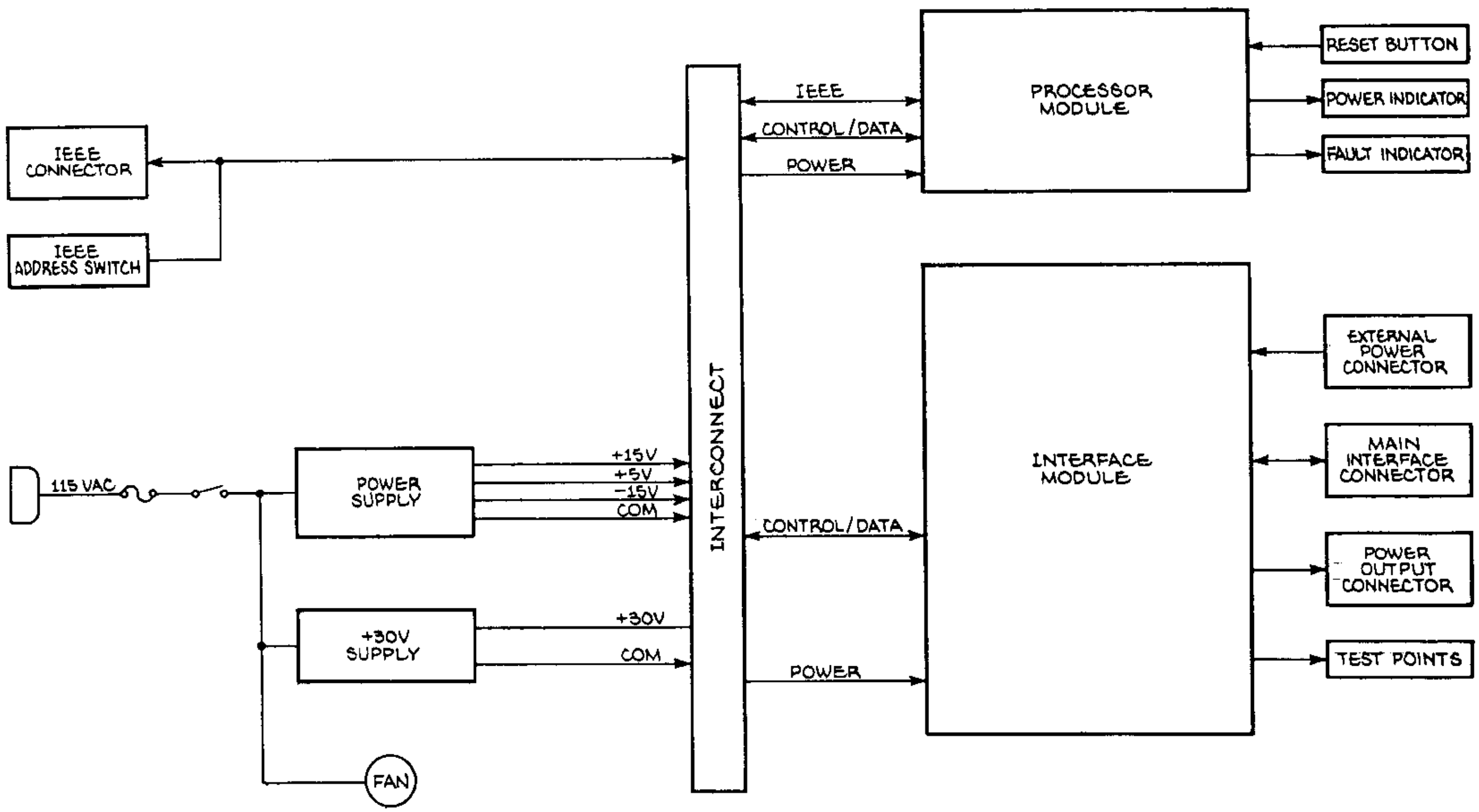

Figure 3 Electrical Interface Block Diagram

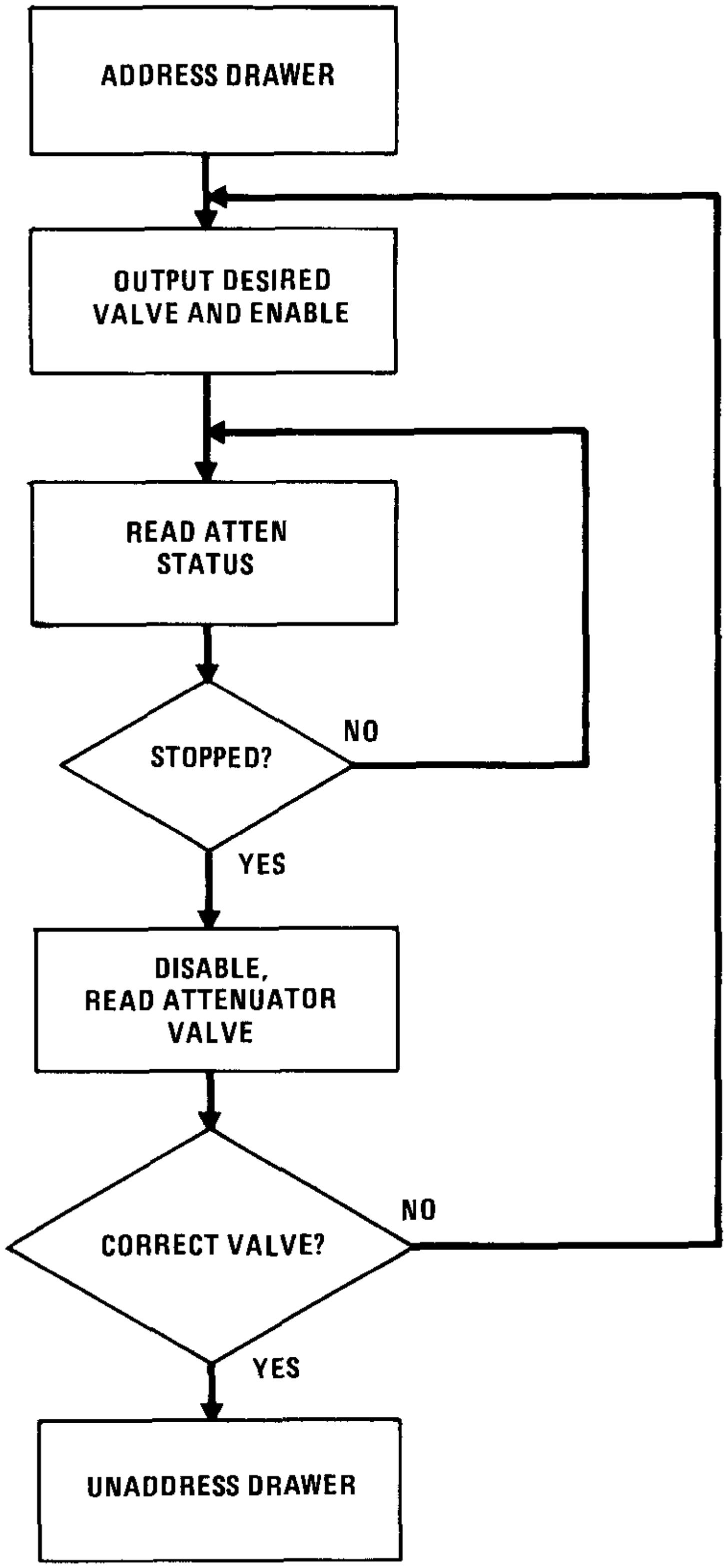

FIGURE 4. ATTENUATOR SET

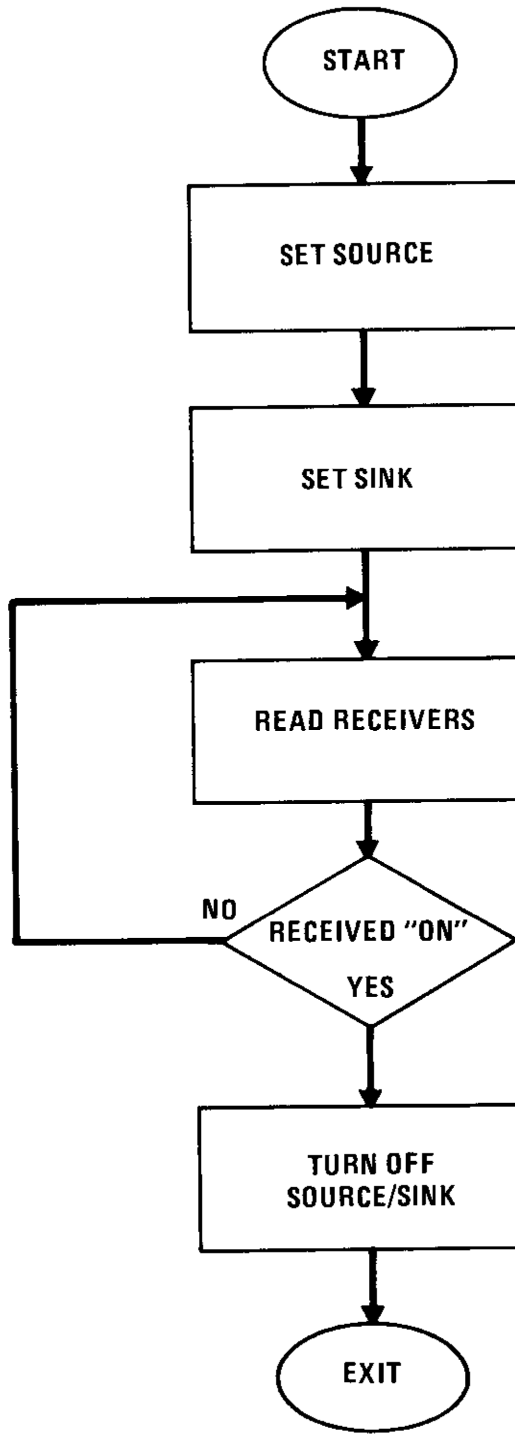

FIGURE 5. RELAY CONTROL

LASER METROLOGY

C. W. Gillard, N. E. Buholz, C-C. Huang, R. H. Anderson
Sensor Technology Department
Lockheed Missiles & Space Company, Inc.
Sunnyvale, California 94086

ABSTRACT

This paper describes the results of research undertaken to develop a number of laser metering systems which, although not developed for general metrology applications, will no doubt become important in the science of measurement. Two of these systems will be highlighted: the first is a laser interferometer capable of making precision absolute distance measurements over extended ranges; the second is a multi-channel interferometer/vibration sensor. Absolute distance interferometry is needed, and was developed, for the precision figuring of large structures; the multi-channel interferometer/vibration sensor was developed to assist with the active (dynamic) control of the extended, lightweight structures being developed for space. Attractive potential uses of this new technology are apparent in many areas of science and industry. Examples include manufacturing, batch process control, machine control, materials research and testing, the control of robots, and the establishment of improved measurement standards.

INTRODUCTION

Laser metrology has had a major impact on the science of precision measurement over the past two decades, since the HeNe laser became commercially available in the early 1960's. This impact is not only continuing, but growing. Laser metrology in the context of applications to manufacturing and process control has interesting implications ... implications which in large measure are responsible for the growing interest in the technology Indeed, it is the applications areas where the science of measurement bears fruit, where its impact is tangible, exciting and can be reckoned in terms of new products and financial rewards.

LMSC has long been active in the development of laser distance and vibration measuring sensors for the active control of spacecraft and space structures such as antennas. Sensors developed specifically to serve these needs include sources based on the CO_2, HeNe and, recently, diode lasers. Detailed background information on these sensor systems, their principles of operation, state of development and demonstrated performance, is available in the literature (see References). This paper will briefly review the capabilities of these systems and illustrate applications possibilities in the areas of: (1) robotics, and (2) active control of large space structures. It is hoped that, by analogy, such applications examples might suggest other, more general uses of the technology.

To conclude this introduction, it is helpful to briefly scope the principles-of-operation of the various sensor systems. Its purpose is to provide a concise perspective to the background discussion of the basic elements of the laser metering systems which will follow.

The CO_2 distance measurement system is based on multi-wavelength interferometry (1,2). It offers the precision inherent with interferometric measurement, and through the use of multiple colors is able to achieve an ambiguity distance in the interferometer of approximately 12.5 m. Distances up to 100 m can be measured to an accuracy of $\pm 0.03\,\mu m$. High power is available with LMSC's special CO_2 lasers (20 watts); by focusing on non-specular metallic surfaces, measurements can be made directly to the surface, eliminating the need to employ special target retroreflectors.

The HeNe laser measurement system employs a modulated subcarrier and precision phase measurement techniques to achieve a distance measurement accuracy of $\pm 25\,\mu m$ (0.001") (3). Analysis shows that by using large target retroreflectors this system can be employed over distances of several km.

The diode laser distance measuring system will, when developed, operate in a manner similar to the HeNe laser system. Laser metrology using diodes is new; it has only recently been made possible through the advent of long coherence length diodes. Work on this promising new area is in the early development phase.

A multi-channel (50 or more) relative distance measuring version of the HeNe sensor has been developed for the dynamic control of large space structures (4). It has a distance measuring resolution of $0.08\,\mu m$, can be used to assist with dynamically removing vibrational energy from large space structures, and is capable of operating out to distances of 100 m. Through the use of redundant channels and readings, a trilateration technique developed by ITEK, but based on the LMSC multi-channel HeNe sensor, can be used to provide accurate, absolute position control of a limited class of structural configurations which permits motion of the target and, thereby, the necessary redundant readings. This class of targets includes, but is not limited to, a target on the arm of a robot.

All of LMSC's laser measurement systems employ heterodyne photodetection techniques. Each is thus capable of sensing not only distance but also vibration. Vibration can be a useful diagnostic for sensing tool wear, breakage and perhaps task completion for robotics and process control. For large space structures vibration measurements are needed for dynamic control.

BACKGROUND

Here, we shall review the basic elements of developed laser measurement systems, and later discuss the use of those systems as building blocks in a robotic positioning and control configuration suitable for automated manufacturing and assembly, as well as for precision control of large space structures.

Absolute Distance Interferometry

Recent developments demonstrating the feasibility of employing laser interferometry to measure absolute distance over extended distances have been reported (1). The results of this work demonstrated a measurement accuracy of 0.03 μm (RMS) over distances up to 10 meters, with a largest ambiguity distance of 12.5 m. A CO_2 laser, specifically designed with the properties needed for this work and capable of operating on several sets of stable R- and P-line pairs, provided the basis for resolving the half-wavelength ambiguity typical of single wavelength interferometers. Stability of the laser is adequate for measurements to 100 m, but for a given distance measurement, the order of the 12.5 m ambiguity distance will have to be known apriori.

To validate and demonstrate the capability of the CO_2 absolute distance sensor (ADS) to make precision absolute distance measurements over extended ranges, a ten-meter optical rail was designed and fabricated of wood. Provision to enable comparison measurements using an H-P Interferometer (Model 5525) was made. Figure 1 schematically illustrates the test configuration. Figure 2 is a photograph of the optical rail test setup. Congruence between the H-P Interferometer beam (HeNe) and the ADS target beam (CO_2) was established using a flat germanium plate as a dichroic beamsplitter. A cable driven carriage supported t' target retroreflector; excursion of the target was a full 10 m. Typical comparison measurement results are shown in Figure 3. The 0.05 μm peak-to-peak spread between the linear envelope lines bracketing the datum points approximately equates to an RMS statistical spread of approximately 0.03 μm.

Laser Beam with Modulated Subcarrier

Distance may be measured by using a modulated laser beam and accurately measuring the phase of the modulated subcarrier on the return beam. Heterodyne photodetection permits the phase measurement process to take place at a convenient electronic frequency, not necessarily the frequency of the modulated subcarrier. By employing multiple modulation frequencies, ambiguities may be resolved in the same basic manner as with the absolute distance interferometer. As an example of this method of measuring distance, LMSC has developed a laser distance measuring sensor employing a HeNe laser source and Bragg cells to establish the heterodyne local oscillator beam. A distance resolution of some 25 μm was achieved using a 400 MHz modulation frequency and a LO offset of 33 MHz. Figure 4 illustrates the elements of the modulated subcarrier distance sensor. Note that the distance measured is the difference between reference and target retroreflectors. This permits common photodetection optics and signal processing electronics to be employed, and hence features common-mode noise reduction advantages. The details of this system have been reported previously (3).

Multi-channel Interferometer

By driving the broadband Bragg cell shown in Figure 4 with a multiple frequency source, the basis for a multi-channel interferometer is achieved. Multiple frequencies both physically separate the beams (for pointing at separate targets) and provide a distinct frequency offset for each target so that the combined optical returns, photomixed on a common photodetector, can be isolated spectrally for signal processing. Figure 5 schematically illustrates a ten-channel interferometer developed to examine and demonstrate the basic features of multi-channel interferometry (4). Figure 6 is a photograph of the prototype ten-channel device. Figure 7 illustrates the simultaneous outputs of four channels of the ten-channel interferometer in response to different vibratory stimuli for each channel. The device could easily be expanded to, say, a 50-channel interferometer. The limitation is the available laser power which must be shared among the desired number of channels, as well as the required signal-to-noise ratio.

It is important to realize that the multi-channel interferometer, unlike the absolute distance measuring sensors discussed previously, is a relative distance measuring sensor; for any given channel, it essentially counts fringes between any two target locations. Reference 5 shows that by simultaneously viewing a single target (attached to a robot, for example) from a number of separate locations (at least 4) that a given target location can be over-specified, and that the redundant information can be used to remove interferometer ambiguities. The result: absolute measurements are possible providing the laser beams are not interrupted.

APPLICATIONS

Robotics

It is anticipated, and indeed logical to expect, that the upcoming growth in robotics will stress software standardization and compatibility with a common data base such as CADCAM. Laser metrology offers a key for unlocking this capability.

Guiding a robot by means of a truss arrangement of precision, distance-measuring laser beams referenced to benchmarks in the vicinity of a manufacturing work station can, through a coordinate transformation, provide accurate, three-dimensional coordinate data on the robot as well as the material to be worked. This approach constitutes a logical extension of the relatively recent laser distance-measuring technology currently being used to enhance the accuracy of N/C machines; it is also consistent with a growing need for compatible, more easily programmed automation systems employing an interdisciplinary data base, such as that created by Computer Aided Design and Computer Aided Manufacturing (CADCAM).

A manner in which multi-channel interferometry might be employed to control a robot is schematically illustrated in Figure 8. Regardless of the specific laser distance measuring system to be used, an absolute distance measuring capability on the part of the system used to track the robot appears to be a *minimum requirement*. The general optical truss configuration suggested in the figure can be varied to suit the specifics of the work area, work piece configuration and the sequence of operations to be performed. Employing LMSC's multichannel interferometer in the trilateration technique developed by ITEK (5) will require a tetrahedral truss baseline rather than the baseline configuration illustrated in Figure 8. For the ITEK scheme, baseline calibration is achieved by taking some ten measurements at different but arbitrary locations of the target attached to the robot "wrist"; the beams then would be required to track the target throughout the manufacturing operation, which would be performed on a "dead-reckoning" basis relative to the baseline reference. If the beams are interrupted, the baseline will require recalibration. Accuracies of the order of 0.2 μm are claimed by ITEK for their measurement scheme when used to measure the surface of a large reflector. Less accuracy would be possible for robotic applications because of the unfavorable geometry, but less accuracy would suffice.

By adding subcarrier modulation to the multichannel interferometer, absolute measurement updates could be periodically provided. Accuracy of the absolute measurements, as mentioned previously, would be limited to approximately $\pm 25\mu m$. Simultaneous tracking of the robot relative to the workpiece would be possible. Accurate calibration of the baseline would be unnecessary, but nonetheless could be easily achieved by directing the tracking mirrors to reflect the measurement beams back to the multi-channel interferometer. With this system, loss of calibration due to beam interruption should be of little consequence since frequent, periodic absolute updates are possible.

The CO_2 system would offer more accuracy than could be justified for robotics (0.03 μm). However, it would also offer high power ... enough to work against non-specular, metallic surfaces. Retroreflectors would be unnecessary. However, such a system has disadvantages: the beam is invisible and difficult to align, the system is large, cryogenic photodetection is required, and automatic focusing would be necessary.

With all of these systems, the scanning mirrors would require both acquisition and tracking modes of operation: open-loop tracking for target acquisition, and closed-loop tracking to more precisely point to a target as well as follow targets which move.

Benefits to be gained through the application of laser metrology to robotics, very briefly include:

- Closed-loop fabrication control via measurements near or about a tool tip, which provides a basis for achieving increased accuracy with unsophisticated robots (i.e., robots with no temperature or stress compensation).
- The ability to interface a common data base with available industrial robots involving a minimum of reconfiguration. The benefits of standardized software procedures may be expected to stem from this ability.
- By means of beam-relay optics it is expected that multiple robots and work areas can be serviced by a common laser metering truss configuration.
- Precision part inspection and checkout, possibly while work is in process, should be feasible.
- Assistance with material movement between processing stations, compensating for floor and work station layout variations, may be expected.
- Laser diagnostics can be used to indicate tool wear (by monitoring cutting head vibration and distance changes to work piece), misalignment and surface finish.
- Parts identification for automatic sorting, using a banded code similar in format to the familiar grocery store universal product code.

In summary, laser metrology, applied to robotics, appears to offer a number of potentially attractive benefits. For a laser-guided robot, the burden of accuracy would be placed on the laser control system; minimum precision would be required of the robot. The result: unsophisticated robots capable of high-precision work. The effects of temperature and stress would have little or no effect on such robots. An ability to interface a common data base, such as CADCAM, to available industrial robots, and the standardized software procedures which would result, may be expected to grow increasingly attractive as automated factories of the future emerge from the prototype investigations and applications studies now underway. Laser-guided robots are coming.

Precision Control and Figuring of Large Structures

A growing need exists for a laser metering system capable of making absolute measurements of the dimensions of large structures. Distances of several meters need to be measured to submicron accuracies. An example of the nature of such measurements might involve a large cylinder fabricated of one of the new metal matrix materials with dimensions of the order of 1 m in diameter by

2 m in length. Such structures are typical of telescope mounts. Measurements of interest might include angular tilt between the ends of the cylinder, length and diameter variations, and decenter (i.e., unequal diagonals not related to tilt). Determination of the thermal properties of such structures, as well as the new matrix materials, may also be of interest (thermal coefficient of expansion as well as possible creep due to thermal cycling). Making such measurements will require a means of establishing fixed reference benchmarks on the structures and a means of making precise (submicron) absolute distance measurements between pairs of benchmarks, a natural application for the ADS system.

A typical application of ADS to a large, segmented mirror system is illustrated in Figure 9. Here, ADS is attached to the same structure as supports the secondary mirror (not shown in the illustration). ADS need not be situated on the axis-of-symmetry of the mirror. For a Cassegranian mirror system, the secondary mirror has a small "blind spot" in the center where a small, two-axis scanning mirror might be attached. The ADS beam could be directed to the scanning mirror from a location behind the primary mirror, if necessary, through a hole in one of the segments. Orientation of the secondary mirror might also be monitored from this location.

A minimum of three targets would be affixed to each mirror segment. The targets most likely would be open retroreflectors, but possibly could be zone-plates etched into the mirror surface. Scanning is not as difficult as it seems, and several candidate scanning methods have been proposed that appear to be acceptable.

Analogous applications to large microwave antenna systems would involve a straightforward adaptation of this configuration. For antennas, however, the HeNe distance measuring system or a variant of the multi-channel interferometer incorporating a modulated subcarrier would be simpler and provide more than adequate accuracy.

CONCLUSIONS

Several new laser measurement concepts have reached a laboratory level-of-development which are destined to have an impact on the science of measurement: (1) absolute distance interferometry (accuracy: $\pm 0.03\,\mu m$, RMS), (2) modulated subcarrier HeNe absolute distance sensing (accuracy: $\pm 25\,\mu m$), (3) multi-channel interferometry/vibration sensing.

Examples of potential applications of these sensors to robotics and to the dynamic control of large space structures ... areas in which laser metrology is being investigated as it appears to offer attractive solutions to the many difficult control problems which are now being seriously studied ... have been reviewed; many logical, convincing arguments in favor of laser metrology are plainly evident, particularly since these are problem areas where alternative solutions simply do not exist. General applications, and possible ways in which these new achievements may be used to advance the science of measurement, are as diverse as the many measurement problems seeking solution. Originating solutions and the many inventions yet to be mothered from necessity have been left to the imaginations of those with problems to solve where laser metrology offers a logical approach.

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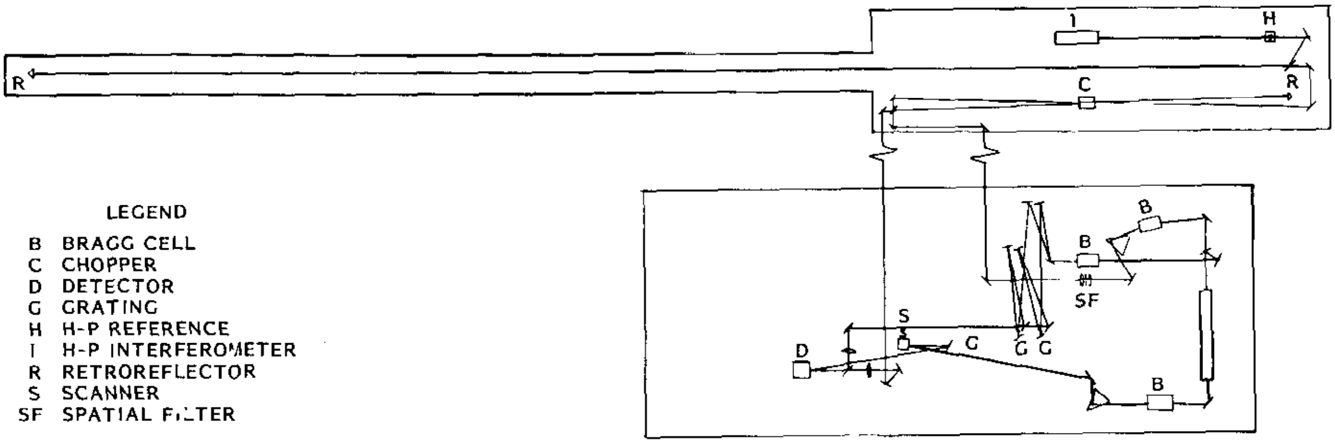

FIGURE 1. SCHEMATIC DRAWING OF ADS BREADBOARD AND TEN-METER RAIL

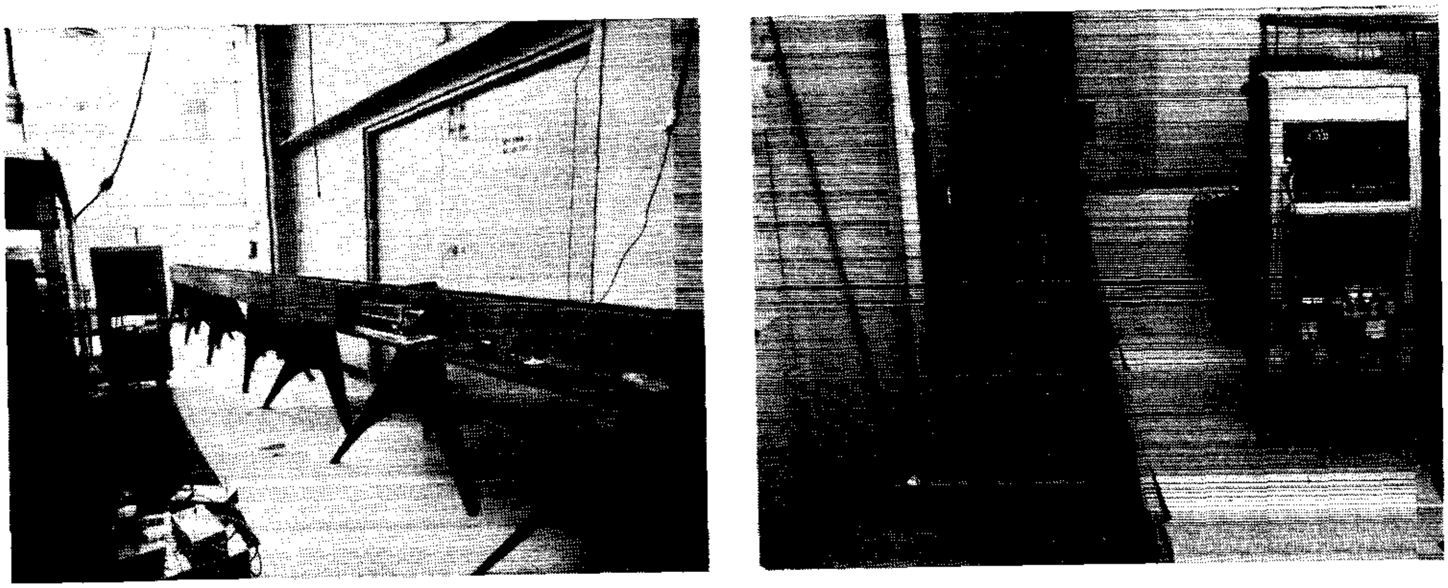

FIGURE 2. TEN-METER OPTICAL RAIL FOR ADS-HP COMPARISON TESTS

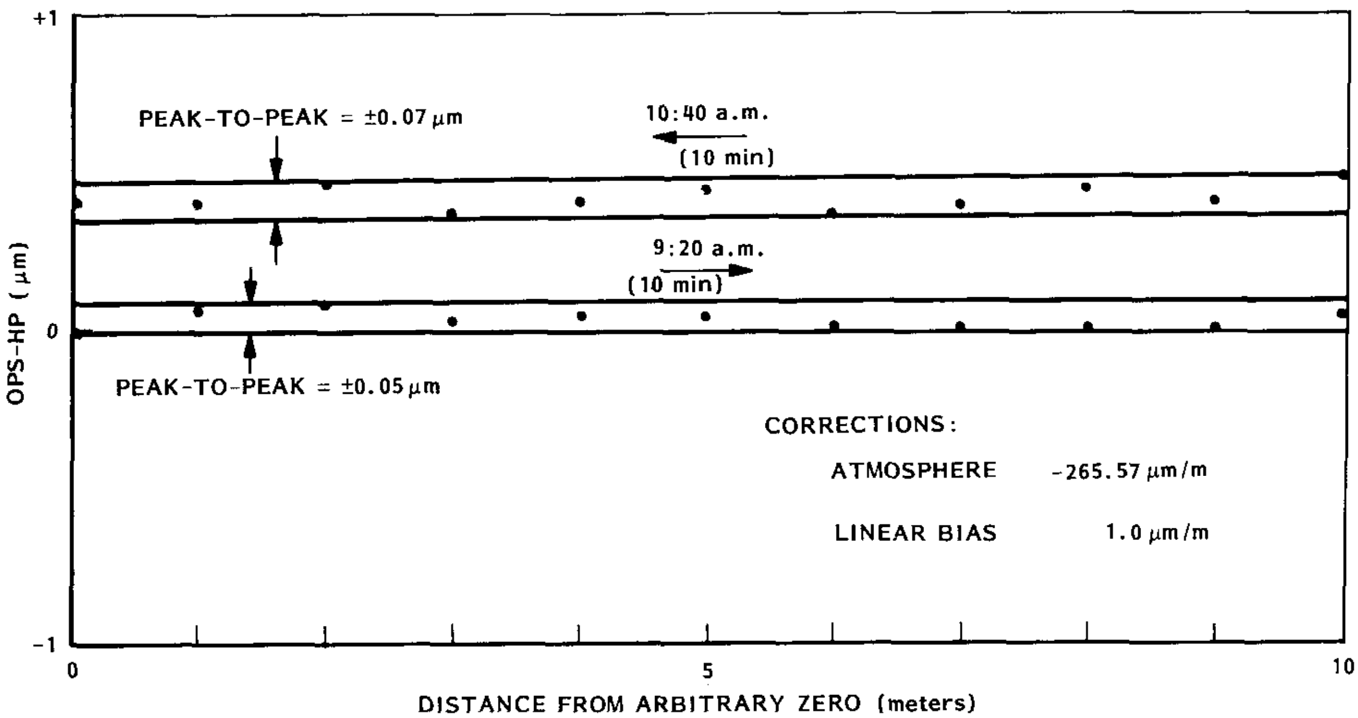

FIGURE 3. ADS-HP COMPARISON MEASUREMENTS

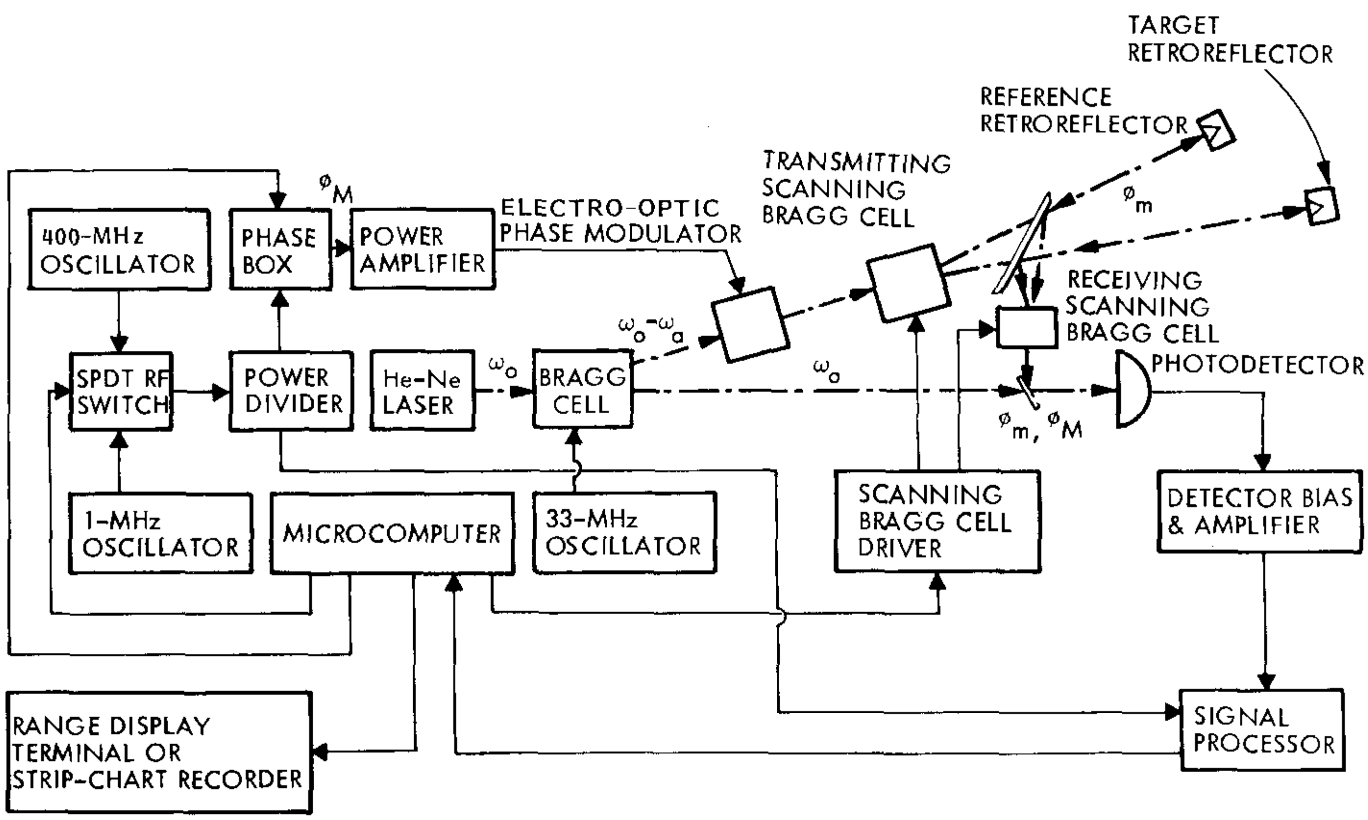

FIGURE 4. DISTANCE MEASURING SENSOR CONCEPTUAL LAYOUT DIAGRAM

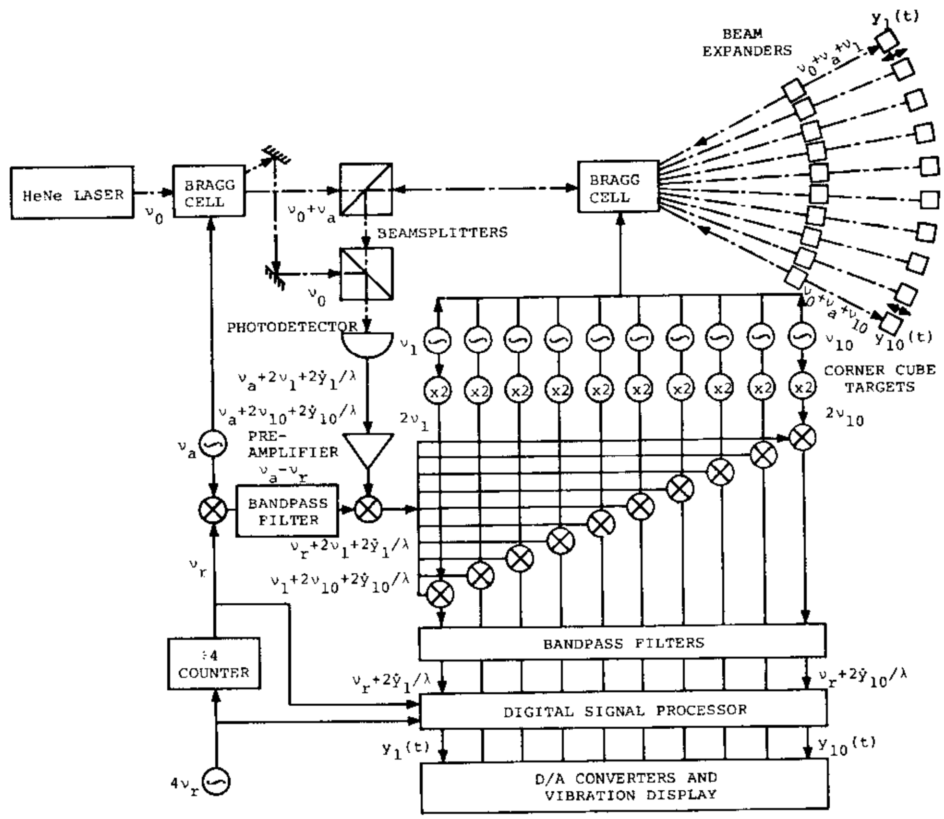

FIGURE 5. SCHEMATIC ILLUSTRATION OF TEN-CHANNEL INTERFEROMETER

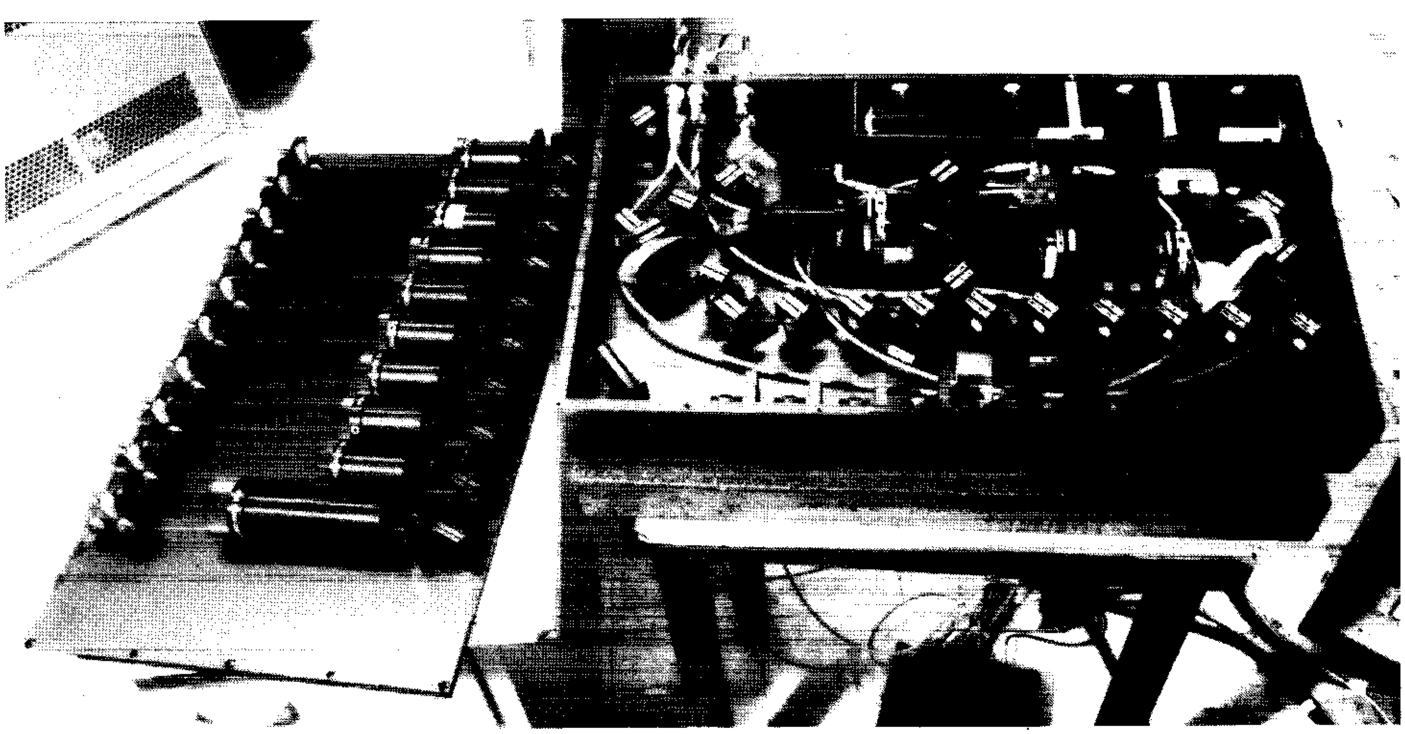

FIGURE 6. PROTOTYPE TEN-CHANNEL INTERFEROMETER

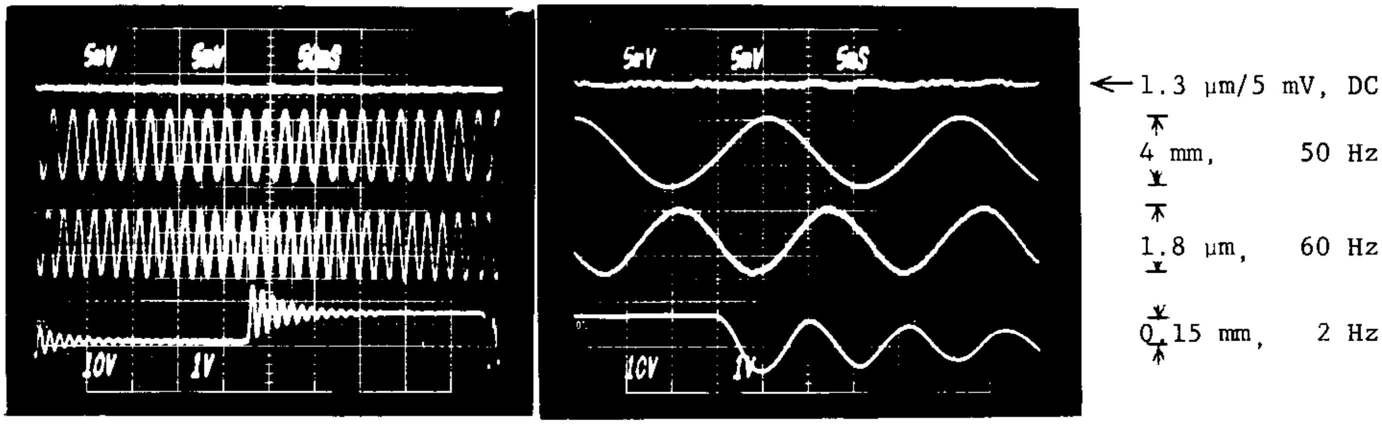

FIGURE 7. SIMULTANEOUS OUTPUTS OF FOUR CHANNELS OF TEN-CHANNEL INTERFEROMETER IN RESPONSE TO A VARIETY OF STIMULI

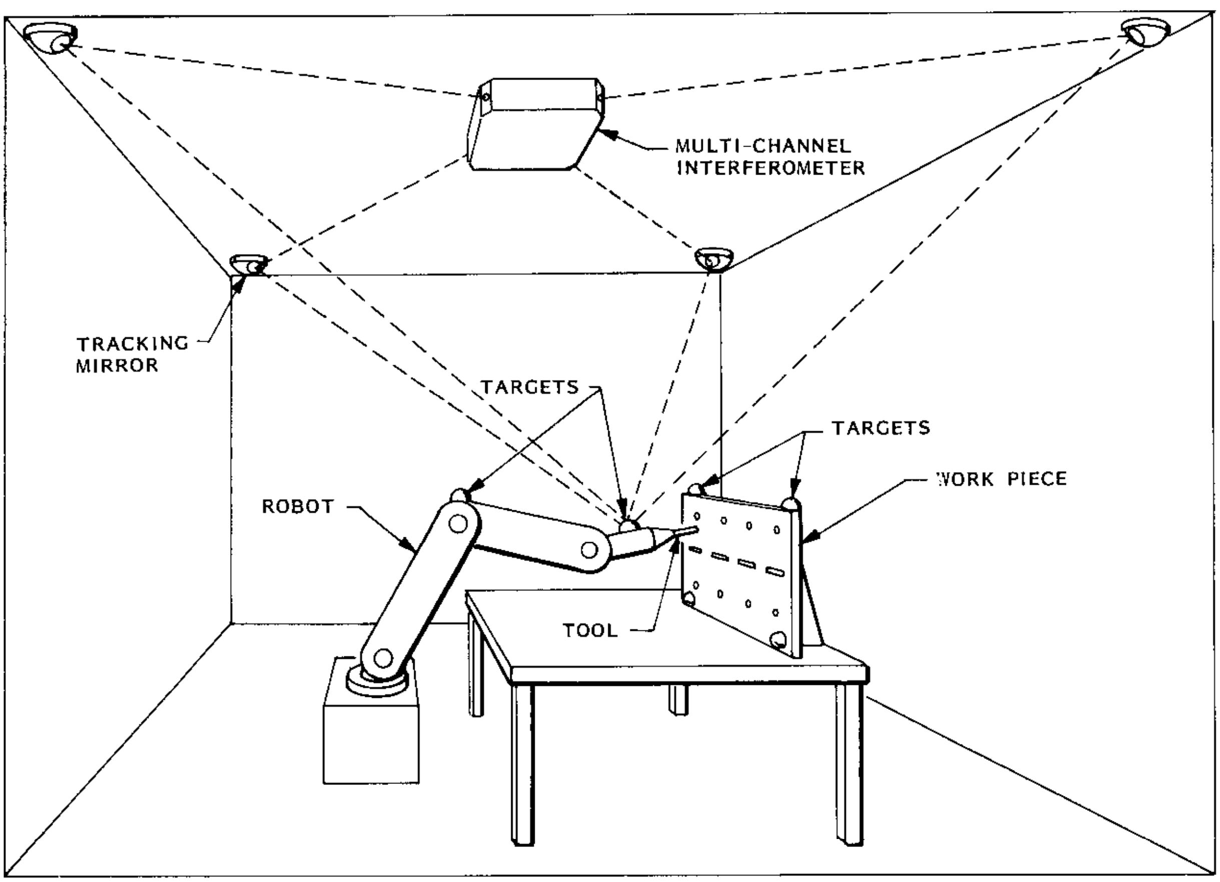

FIGURE 8. ROBOT CONTROLLED BY LASER INTERFEROMETRY

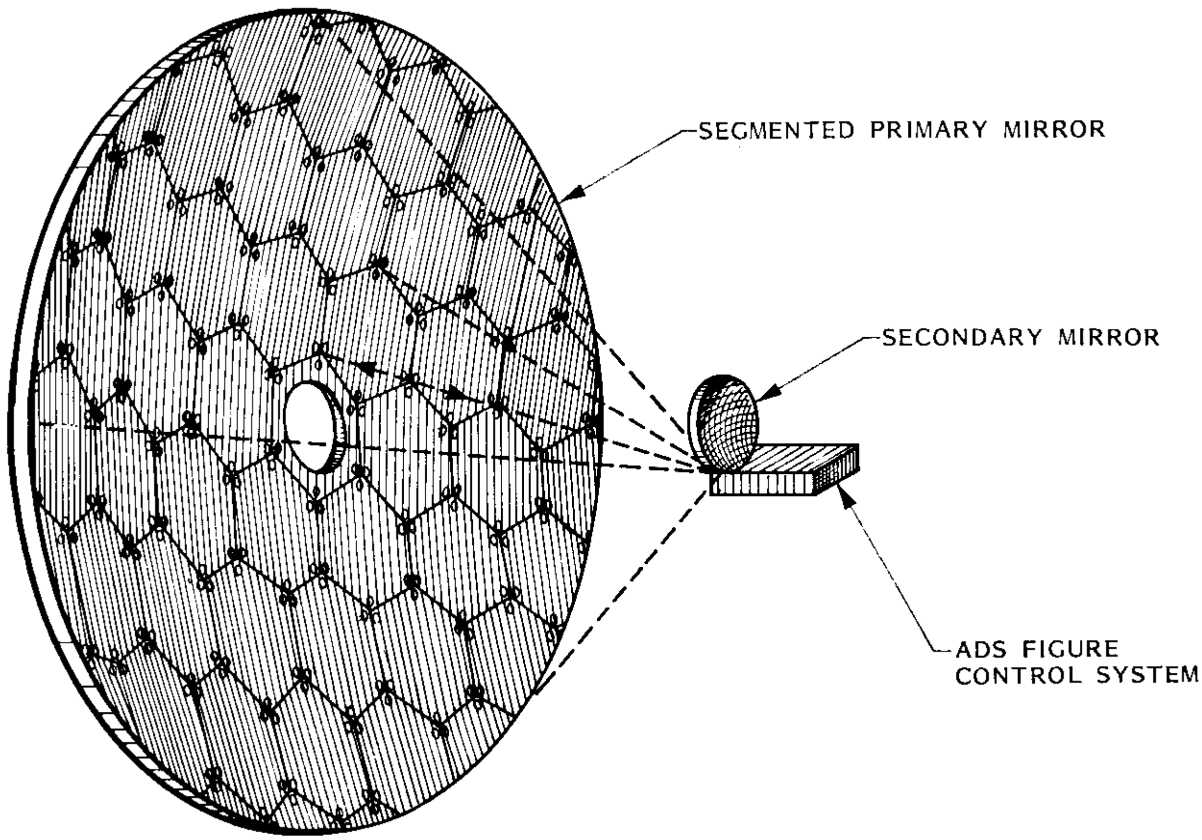

FIGURE 9. SCHEMATIC ILLUSTRATION OF ADS FIGURE CONTROL SYSTEM EMPLOYED TO MONITOR EDGE AND SURFACE TARGETS OF A MULTIPANEL TELESCOPE

LASERS ROLE IN MODERN OPTICAL METROLOGY

John J. Lee, Jr.
Electro -Optical Physicist
General Dynamics/Convair
San Diego, California

ABSTRACT

Optical Metrology has in recent years had a rebirth primarily due to the development of laser systems. This paper discusses two of the roles lasers play in modern optical metrology. First, the laser as a research and manufacturing tool must be characterized and calibrated. The calibration needs and basic characteristics of several lasers will be defined and discussed. Second, several examples of the laser as a measuring tool will be discussed.

INTRODUCTION

One of the major emphasis of the newly developed Optical Metrology Laboratory at General Dynamics/Convair has been to solve the calibration problems of laser systems. Lasers have become so well established in electro-optics that many systems are in use without proper calibration. This is not only true of Research and Development labs, but also in manufacturing, production and quality. Currently, calibration procedures, techniques, and test sets are being developed so that the inadequate calibration problem will be solved.

The laser has also become a well accepted and reliable tool for dimensional measurement. For many applications, an optical straight edge is the best measurement choice. Currently, several laser systems are being used for dimensional measurement and calibration.

LASER CHARACTERISTICS

To calibrate laser systems there must be an understanding of the basic characteristics lasers possess. A laser (light amplification by stimulated emission of radiation), is basically an optical oscillator. It consists of an amplifying medium, inside of an optical resonator or cavity, which is pumped by some type of external excitation. The laser oscillation acts as a standing wave inside the cavity, with an output of a highly monochromatic collimated beam of radiation. The laser possesses three important properties: monochromaticity; temporal and spatial coherence; and certain beam qualities.

Monochromaticity is in reality the oscillation band width of the laser and therefore determines the frequency or wavelength of the laser output. It is due primarily to the fact that oscillation, and therefore amplification, can only occur at the resonant frequencies of the cavity. In practice, cavity changes, due to thermal expansion or vibration, are the practical limits to frequency stability.

Laser outputs are both temporally and spatially coherent. Temporal coherence means that the laser output will interfere constructively at any given point at two different times. Spatial coherence is where the laser output interferes constructively at two separate points at the same time. This property accounts for many of the applications for which lasers are being used.

The output beam possesses several important qualities: First, it has a high degree of directionality with a small divergence angle; Second, it has a known polarization for a given frequency; Next, the beam has a high brightness or radiance due to its directionality; Last, the output beam consists of transverse electromagnetic modes.

LASER CALIBRATION

The calibration of laser systems have many measurements in common, yet each has its own particular calibration needs. In many laser systems the most important parameter is the frequency or wavelength of the output. This can be particularly true for lasers, such as CO_2, which will lase at several different transitions with a small change in cavity length or temperature. Many devices have been developed to monitor and measure laser frequency - most of which are based on some type of grating technique.

Output power (energy) is another important consideration for laser system calibration. Due to the diversity of laser systems, power must be defined to include peak, average, and pulse power. Each of these measurements must be done separately using various techniques. Such devices as calorimeters, radiometers, photodetectors, etc. have been developed for these measurements.

Polarization, mode and divergence angle are all beam qualities that have a secondary calibration need. In most instances these parameters are not an important consideration, but in some specialized systems each can become system limiting. The divergence angle only becomes important when dealing with small apertures or the beam waist and therefore is seldom a problem. Polarization becomes important anytime a polarization dependent element (modulators, $\tau/4$ retarders, $\tau/2$ waveplate, polarizer, etc.) is in the system. In this instance, if polarization changes, the signal or beam can be completely lost, or at least, the power will fluctuate. The laser mode can also affect power fluctuations. A change in the laser mode will cause both power fluctuations and a change in the cross sectional power density of the beam. In the case of a TEM_{00} the power density is a Gaussian distribution centered on the optical axis. For each of the other transverse electromagnetic (TEM) modes, the power density distribution can be calculated but is more complex. A few devices exist for examining laser modes, pyroanalyzers and thermal imaging techniques, but viewing of the farfield beam gives a good idea of the laser mode.

Each of the preceding characteristics are important in the calibration of laser systems. The accepted monitoring technique is not to make instantaneous measurements but to look at both the short and long term stability of the system. In this case, short term usually is of the order of a few minutes, whereas long term is approximately an hour. Each of the systems parameters (frequency, power and beam qualities) must be measured for stability and are usually specified as such by the manufacturer.

In many cases, the laser system under test has specialized components which directly affect the output. Examples of such devices include: active cavity control - cooling, PZT, dither stabilizer, etc.; internal modulation; Q-switch techniques; mode lock techniques; and internal gratings to name a few. These components create specialized calibration procedures depending on the type of laser and the combination of specialized components. Following are two examples of laser systems, their basic parameters, and general calibration techniques.

HeNe LASER CALIBRATION

The HeNe laser is one of the most popular and widely used of all lasers. (Figure 1) It is a neutral atom gas laser with a four level pumping scheme. Laser action occurs between the neon energy levels with helium added to assist in the pumping process through resonant energy transfer. (The 2^3S and the 2^1S energy levels of helium and neon are resonant). The HeNe laser can oscillate at any of three different wavelengths; 3.39μm; 0.6328μm; and 1.15μm. (Figure 2) The wavelength for a particular HeNe laser can be chosen primarily by the proper choice of reflectivity for the dilectric mirrors or by inserting Brewster windows into the cavity. The 0.6328μm HeNe laser is by far the best known and most used laser in industry today.

The HeNe laser has optimum values for many of its operating parameters. Since de-excitation is primarily due to atoms colliding with the walls of the laser tube, the optimum tube diameter is approximately 2 mm. The optimum Ne pressure is approximately 0.1 Torr with a ratio of He/Ne of 5 - 10. An optimum discharge current density also occurs and creates an optimum discharge length and power. (For a tube approximately one meter in length the output power is on the order of a few milliwatts.)

Frequency stability for HeNe lasers can be accomplished several different ways. The easiest is to use a Lamb dip technique with a feedback circuit. Basically this technique locates the bottom of the Lamb dip, which is very well defined, and keeps the laser on that frequency. Stabilities and reproducibilities of one part in 10^9 have been accomplished with this technique. Another basic technique is to use a saturated absorber inside the laser cavity. Frequency stabilities on the order of one part in 10^{13} have been accomplished using this technique.

The calibration and characterization of HeNe laser systems is in general quite basic since most manufacturers use optimum operational parameters. The measurement of laser wavelength only becomes important in very precise systems such as the Hewlett-Packard Laser Measurement System. (In this case, a wavemeter or spectrometer can be employed). Output power degenerates very rapidly but can be monitored by using conventional detection techniques. The divergence angle, mode, and polarization of HeNe lasers become the most important parameters for system calibration. Both the divergence angle and mode can be measured and characterized by visual techniques in the farfield Polarization can be easily measured using conventional polarizing elements and power detectors. Due to the complexity and lack of adjustments, on most HeNe lasers, there is little except characterization that can be performed.

CO_2 LASER CALIBRATION

CO_2 lasers are quite complex and, unlike HeNe lasers, have many possible adjustments. Since there are many different types of CO_2 lasers, (gas flow, sealed, TEA, RF Waveguide, D. C. Waveguide, etc.), the discussion here will be limited to D. C. excited continuous wave waveguide CO_2 lasers. (Figure 3).

The CO_2 laser is a molecular laser that is dependent upon vibrational-rotational quantum mechanical phenomena. The laser consists of a mixture of several gasses, (CO_2, CO, N_2, HE, and XE), with manufacturer's combinations seldom the same. In general, the mixed gasses, to the CO_2, are to improve efficiency by producing large population inversions by resonant energy transfer, or to cool the CO_2 molecules by transferring energy to the laser walls. Since CO_2 is a triatomic molecule, there are three distinct modes of vibration, (A discussion of this problem can be found in most laser texts), and laser action occurs between these vibrational levels. (Figure 4) For this reason, the CO_2 laser is able to lase on many lines, in the IR regime, and is somewhat difficult to stabilize the frequency for a long time period.

The waveguide CO_2 laser consists of a small capillary discharge bore (~1 mm) cavity, usually of a dielectric material, that acts as a waveguide for the laser beam. The cavity is sealed off and is filled with a high pressure gas mixture. The gas is excited by a high voltage discharge, through the gas, in one of many configurations. Most waveguide lasers have active cooling, usually in the form of forced air, along with a number of possible speciality options. These include: Dither stabilizer for frequency stability; gratings for laser line tuneeability, PZT for cavity length changes; polarizers for polarization stability; and a host of other speciality options.

The calibration and characterization of CO_2 laser systems can, even for very basic systems, encompass numerous measurements. Due to their complexity, and a lack of vendor standardization, a general calibration procedure is difficult at best. The following paragraphs will try to explain the most necessary measurements and some of the important considerations when characterizing such systems.

Frequency stability, and therefore wavelength stability, for CO_2 waveguide lasers is usually poor. Typical vendor specifications for a temperature stabilized laser, with constant line voltage, are: short term (minutes) $\pm 1 \times 10^{6}$; long term (hours) $\pm 1 \times 10^{5}$ (With specialized dither stabilization the laser frequency can be stabilized to $\pm 1 \times 10^{7}$ or $\pm$ 3 mHz. Instability is normally caused by cavity length changes, due to temperature effects, but can also be caused by laser mode hopping. Since the wavelength transitions are widely spaced, between 9μm and 12μm, an optical spectrum analyzer is the easiest monitoring device. If higher precision is needed, some type of wavemeter or spectrometer in the infrared regime, can be employed.

Frequency instability and temperature fluctuations cause power or amplitude instability. For basic waveguide systems, with no temperature control, typical vendor specifications are: long term (hours) ±10%: short term (minutes) = 4%. With temperature control: long term ± 2%; short term ± 1%. If dither stabilization is used, to stabilize the laser frequency, even better amplitude stability should evolve. Since power fluctuations are quite easy to measure, using colorimeters and radiometers, power is usually used as the monitoring parameter.

Polarization and mode changes are two other parameters that must be characterized. Polarization is very dependent on which line, wavelength, the laser is on. With a change in frequency, or laser line, the angle of linear polarization will change - for a given line there is a given polarization. The typical specified mode, for waveguide lasers, is a EH_{11}, which corresponds to a TEM_{00} in free space, but other mode regularly occur. Typically the only way to change the mode is to cause a frequency shift, through a change in operating temperature, or to go inside the cavity and change the D. C. discharge. The mode can be easily measured in the farfield with phosphorescent targets or a pyroanalyzer. To measure polarization, the use of polarizing elements together with a power measurement is an easy technique.

LASER INTERFEROMETER

Interferometers are an important application of lasers because they provide a stable coherent source of quasi-monochromatic light. Applications abound for interferometers and thus many types have been designed. Basically, an interferometer compares the phases of two coherent light beams that have different optical paths from the same source to a common test object Such measurements as distance, surface flatness, chromatic aberations, transmission, etc. are easily attainable using interferometric techniques.

Currently, an older model Zygo interferometric system is being used for a variety of measurements. The system has a 12" aperture capability and is configured as a Fizeau interferometer. The basic use of this system is to measure, in situ, surface figure of large aspheric carbon/carbon laser mirrors. (Figure 5) Another use of this system is to measure transmission aberations of optical lenses used for several research projects. A new interferometer is being developed for transmission and other measurements using a CO_2 laser, at 10.6μm, rather than the current Zygo that uses a HeNe laser at .6238μm.

DIMENSIONAL MEASUREMENT SYSTEM

The calibration of coordinate measuring machines and large numerically controlled machines has always been a long and tedious job. With the incorporation of the Hewlett-Packard Corp. 5526A Laser Measurement System, these calibrations have become routine. There are currently two H. P. Laser Measurement Systems, on a full time basis, doing the aforementioned calibrations along with other dimensional calibrations. These systems are able to measure angle, flatness, straightness, perpendicularity, and linear measurements with 0.01μm resolution, (±0.5 parts per million accuracy), over a measurement range of up to 61 meters.

The Laser Measurement System works on an interferometric technique with a slight twist. The system emits a coherent light beam composed of two slightly different optical frequencies, caused by a Zeeman splitting inside the laser head, with opposite circular polarizations. By linearly polarizing this beam, two orthogonal linear polarizations are created. A pick-off beam splitter is used to create a reference beam for the counter and for tuning the laser cavity. The linearly polarized beam is then split into the two separate frequencies, each directed toward its own retroflector, combined again and returned to a photo-detector in the laser head. Relative motion between the retroreflectors causes a doppler shift, this difference is monitored by a fringe-counter, and through multiplication and conversion, the displacement is displayed.(Figure 6) Using several different interferometric techniques the system can produce all the aforementioned dimensional measurements.

LASER MICROMETER

Lasers have been used for dimensional measurement for many years and have continued to improve both in speed, accuracy and repeatability. Currently, a Techmet "Laser Mike" is being used for many of the standard micrometer measurements in the dimensional measurements lab. This device, Model 83-00 (Figure 7), with certain modifications, can measure a part from .015" to 1.25" with a resolution of .00005". The "Laser Mike" system has been found to be faster, more cost effective and has better repeatability than the usual measurement technique of using a Standard Measuring Machine.

The technique used by Techmet is known as shadow casting. A parallel scan of the laser beam creates a shadow of the part under test. The scan is then imaged onto a photodetector and with the aid of a microprocessor, a diameter measurement is displayed.

The scan rate is adjustable, but is typically 100 scans per second. Thus, a statistical averaging occurs for each part under test and repeatability is good since most human error has been removed.

Currently, a new system is in development to measure, classify, and sort drill bits. A Techmet "Laser Mike" will be fitted to a robic arm with a chute feedings system. Basically, the robotic arm will grab a drill bit, push it to a stop in the "Laser Mike", turn the bit 360°, get a reading from the microprocessor, and place it in the correct sorted bin.

REFLECTANCE MEASUREMENT SYSTEM

Reflectance, from smooth and rough surfaces, of laser radiation is an important measurement for many military applications. The characteristics of laser reflectance, at 10.6μm, are being studied using several different experimental configurations. An example is shown in Figure 8. These measurements, both diffuse and specular reflectance, can be used for calibration of CO_2 laser sensors along with target characterization.

Two major problems arise in the measurement of laser reflectance. First, due to the directionality of the laser, all reflectance measurements are directional or must be made in a bi-directional configuration. (This can be done by the collection of radiation over a hemisphere). Second, the phenomena known as laser speckle causes measurement problems whenever working with rough or diffuse surfaces. Several techniques are being explored to overcome these measurement limitations.

CONCLUSION

The advent of the laser has created a new thrust in optical metrology both in the calibration of laser systems and in the use of laser systems for precise measurement. The newly developed Optical Metrology Laboratory at General Dynamics/ Convair has only begun to look into these calibration problems and developmental areas. As laser technology changes, the growth of optical metrology is assured.

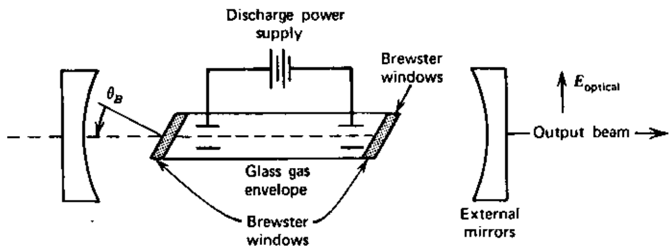

FIGURE 1.

TYPICAL HeNe LASER

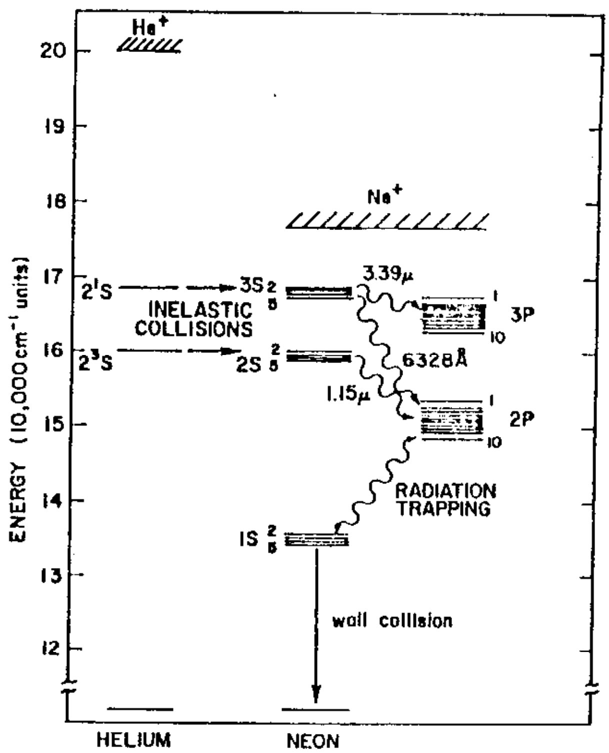

FIGURE 2.

ENERGY LEVEL DIAGRAM FOR THE HELIUM - NEON LASER

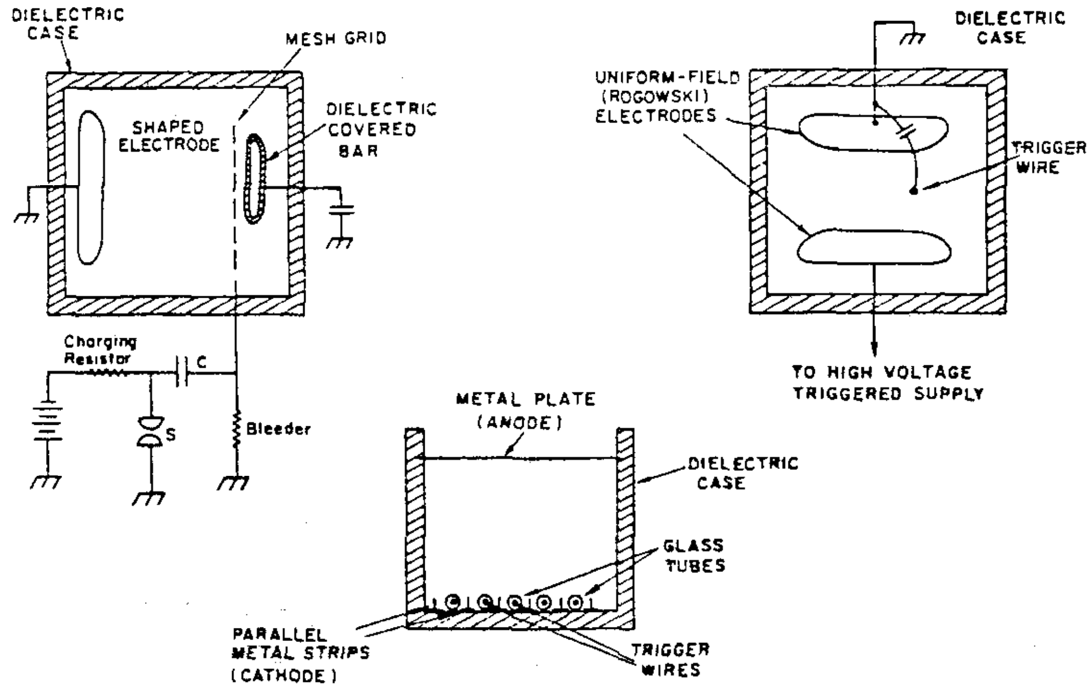

FIGURE 3.

WAVEGUIDE CO_2 LASER DESIGNS

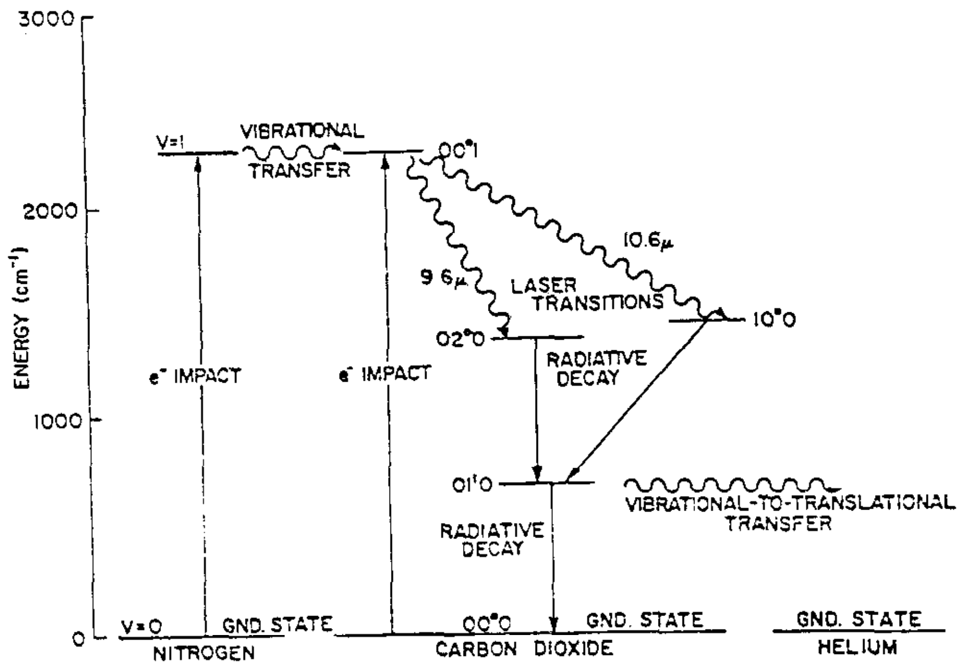

FIGURE 4.

ENERGY LEVEL DIAGRAM FOR A BASIC CO_2 LASER

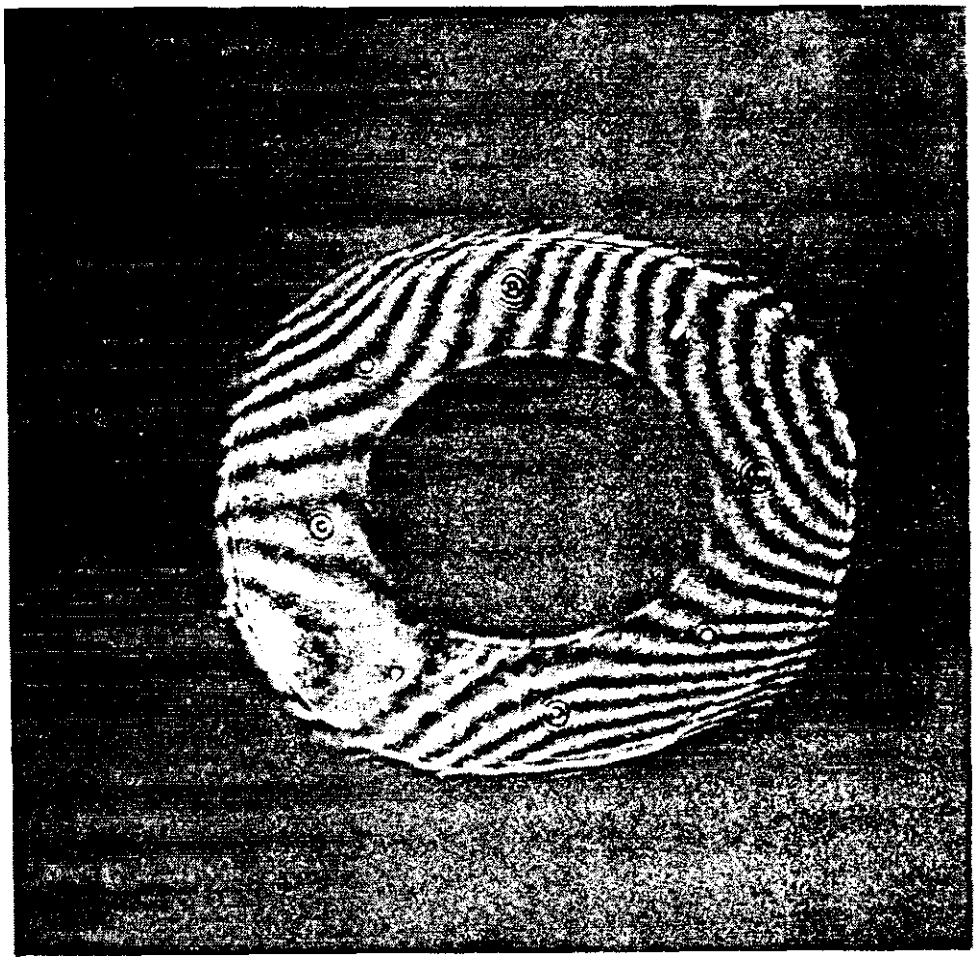

FIGURE 5.

PRELIMINARY INTERFEROGRAM OF A 30 CM CARBON/CARBON MIRROR

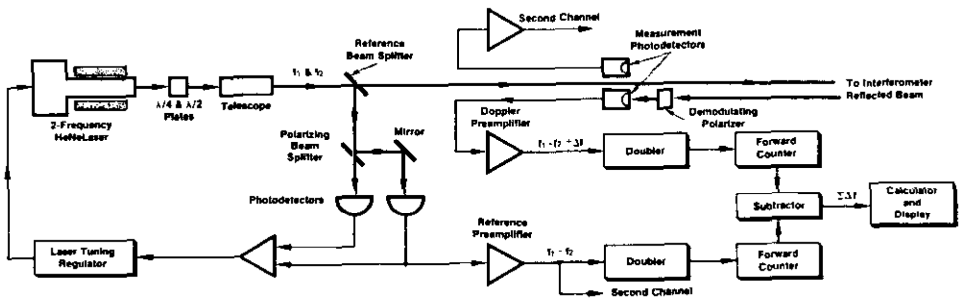

FIGURE 6.

H.P. 5526A LASER MEASUREMENT SYSTEM SIMPLIFIED BLOCK DIAGRAM

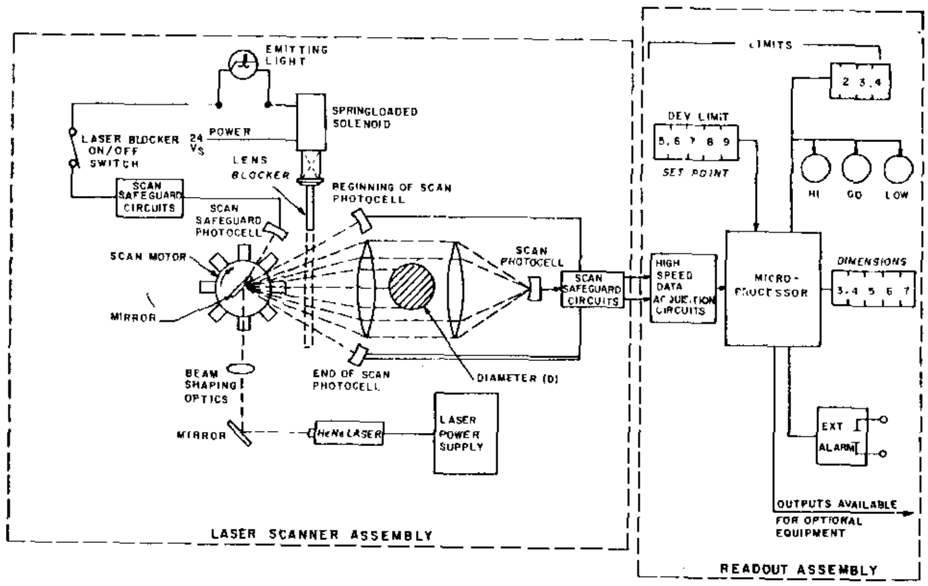

FIGURE 7.

TECHMET "LASER MIKE" FUNCTIONAL BLOCK DIAGRAM

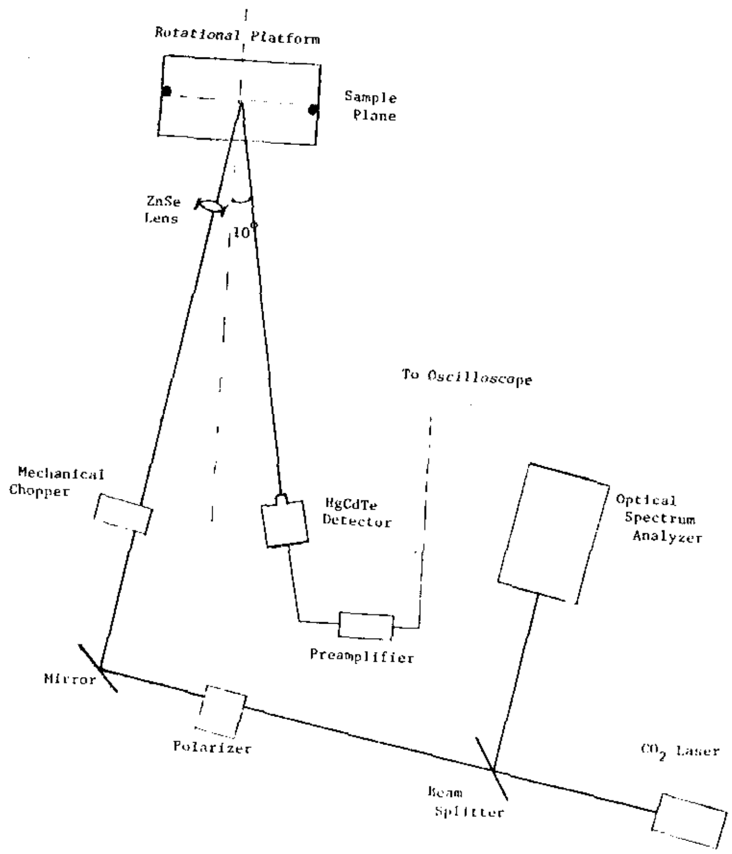

FIGURE 8.

REFLECTANCE MEASUREMENT CONFIGURATION

WHY IS IEEE-488 SO POPULAR

George C. Stanley
Hewlett-Packard Company
1819 Page Mill Road
Palo Alto, CA 94304

ABSTRACT

IEEE-488 was introduced in 1975 and today there are close to 2000 products which conform to this interface standard. This paper examines interfacing problems prior to IEEE-488 and the solutions provided by the standard. Key technical specifications are examined with emphasis on what sets their technical limit and how these limits can be extended if necessary.

INTRODUCTION

IEEE-488 had its beginning in 1965 when Hewlett-Packard decided to standardize the interfacing of all their future products. Prior to the introduction of IEEE-488 a user putting together a measurement system had to find instruments that would make the measurements he wanted and then hope that they had some sort of interfacing capability. Often they did not. At this point in time interfacing was considered a high-speciality item and not something that usually came with off-the-shelf instruments. Adding interfacing hardware to an existing product was often difficult and sometimes impossible. An example of the type of problem a system engineer faced was a computing counter that was designed for system use. This counter had interfacing capability but had 163 unique lines which had to be individually interfaced. This type of situation led to extra costs and interfacing complexities for each product because there was no common interfacing arrangement, i.e. no common connector, no common cabling pin arrangement, and no standard signal or logic level.

Before IEEE-488, software costs were estimated to be at least 2X the hardware cost and this was a relatively conservative number. Often because of unexpected problems, software costs rose to 5X or more the hardware costs. Although these estimates are quite speculative, after IEEE-488 was introduced typical costs were often below or equal to .5X the hardware costs. On top of that system hardware costs have been coming down because most of the special fixturing, cabling and interface processing has been eliminated.

The acceptance of IEEE-488 was aided greatly by the arrival of the "friendly" desktop computer as it used an interpretative-language operating system instead of the more traditional compiled-type operating system. An interpretative operating system is one where each line of code is checked for errors at the time the programming line is stored. Even though this process is slightly slower than the compiled process where the program is compiled once after it is written, it greatly simplifies the writing of computer programs by non-computer trained personnel such as test and measurement engineers. A further help to the acceptance of IEEE-488 was the intelligent or "smart" instrument that allowed the instrument to do many of the things by itself that previously were done step-by-step by the computer. The result of all these factors is that today, at the end of 1982, there are close to 2000 products available that can be interfaced via IEEE-488.

TECHNICAL CONSIDERATIONS

IEEE-488 defines a bus structure that has three basic parts. There is the data bus, which consists of 8 data lines (DIO 1-8), and the control bus, which consists of 5 control lines (IFC, ATN, REN, SRQ, and EOI). Finally, there is the handshake bus consisting of 3 handshake lines (DAV, NRFD, and NDAC). Summarizing the interface technical specifications:

No. of devices - 15 max (incl. controller)

Signal lines - 8 data and 8 control

Data rate - Up to 1 megabyte/sec

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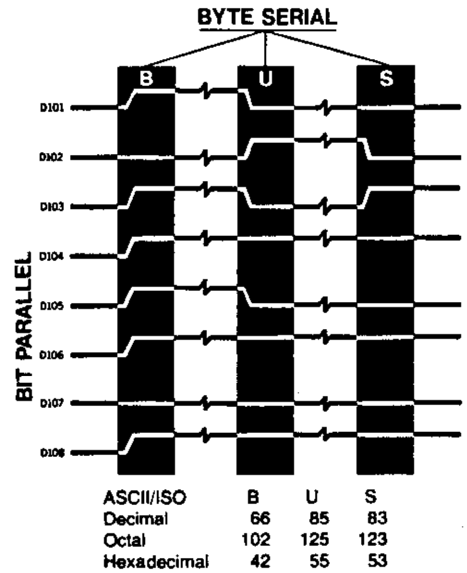

FIGURE 1. IEEE-488 Data Structure

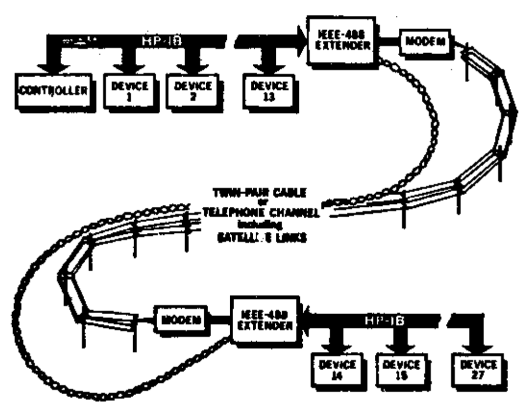

FIGURE 2. IEEE-488 Distance Extenders

Data transfer - Byte serial, bit parallel, bidirectional, inter-locked handshake

Transmission path - 2 meters x the number of instruments up to a maximum of 20 meters

A few comments on these specifications are in order. The limit of 15 devices was selected using three considerations. The first was that discrete component drivers were desired with drivers and loads located in each instrument. This would allow complete flexibility as to cabling. At the time the standard was prepared, discrete low-cost drivers had a current-drive capability that would handle 15 instruments in parallel but not much more. The second consideration was whether or not a 15 instrument limit was realistic. Studying many existing systems indicated that 15 was a very practical upper limit as typically that was a three-bay system. The last consideration was how difficult it would be to go beyond the 15 limit if required. Since this only entails the addition of one more interface card and virtually no programming changes, it was felt that this was a very workable limit.

The data rate of up to 1 megabyte/sec is only achieved if the cabling is restricted to 1 meter/instrument and tri-state drivers are used. Since virtually no instrument operates at this speed, this interface limit on data transfer has rarely been a problem.

Data structure is byte-serial, bit-parallel and is shown in Figure 1. The important points are that data is bidirectional, meaning it can flow either way on the bus, and that a handshake occurs after *each* data byte.

Transmission path length has a double restriction. It is either 2 meters x the number of instruments or 20 meters total, *whichever is less*. To understand why there are two restrictions, keep in mind there are drivers and terminations inside each product. Therefore, when there are few products involved, the termination impedance is relatively high and there is the possibility of standing waves (peaks and nulls) on the cables. As more instruments are added, the line termination impedance drops and more current flows into the lines.

Eventually the reduced termination resistance plus the combination of signal-to-noise plus the cable resistive losses become dominant.

If necessary, the distance limitation can be overcome by using distance extenders as is shown in Figure 2. Here, speed is traded for distance as the byte-serial, bit-parallel structure is converted to a serial format. Typical extenders today are completeley transparent and full duplex. They are fairly sophisticated and provide against errors introduced by poor quality data-circuit problems such as dropouts, line breaks, and sync loss.

SUMMARY AND CONCLUSION

IEEE-488 and its equivalent international standards represent one of the most successful standards ever published. More than 30,000 copies of IEEE-488 have been sold with 30% of these outside the U.S. It has been translated into nine languages and by any analysis has been one of the most significant system events of the past decade.

THE EFFECTS OF IEEE-STD 488 INTERFACE DESIGN TRADE-OFFS ON INSTRUMENT PERFORMANCE

NORBERT LAENGRICH
INTERNATIONAL MARKETING MANAGER
RACAL-DANA INSTRUMENTS, INC.
IRVINE, CALIFORNIA

ABSTRACT

This paper covers trade-offs of different IEEE-STD-488 interface designs from the test equipment user's viewpoint. Brief descriptions are given of the interface circuit design using discreet components, software, and some popular LSI interface chips. These are followed by a review of how the designs effect the performance of the instruments when used in an ATE system. A summary lists several of the most popular LSI IEEE-STD-488 chip sets available.

INTRODUCTION

Since the adoption of the IEEE-STD-488 in 1975, instrument manufactureres have used a variety of circuit designs to implement the interface into their products. Soon after the standard was published, IEEE-STD-488 to BCD adapter assemblies allowed older BCD instruments to work on the new bus. Many of these adapter type interfaces used a microprocessor to control the GPIB (IEEE-STD-488; General Purpose Interface Bus) handshake routines. These GPIB adapters were, by todays standards, expensive and generally were slow in handshaking data over the bus. To improve speed, second generation circuits were designed using discreet IC components. As the demand increased, major semiconductor manufacturers converted these designs to LSI. By 1982, most new products including the IEEE-STD-488 interface (GPIB) use an LSI design as the basis of the interface circuit. The purpose of this paper is to explore how this evolution of circuit design effects the instrument user and ATE system designer.

EARLY MICROPROCESSOR BASED INTERFACE

An example of an early GPIB interface design is the Racal-Dana Model 55, GPIB to BCD Interface Adapter. Introduced in early 1975, this represents a first generation type design approach.

Using a 4004 (4-bit) microprocessor, the handshake function was controlled through ROM software by the microprocessor. The circuit shown in figure 1 implemented the Talk/Listen handshake and address setting functions. In this design, the 4004 microprocessor (U3) combined with memory and clocking chips control the status of each handshake line. Two ROMS (U18, U17) are dedicated to controlling (U18) and sensing (U17) the NDAC, NRFD, DAV, and ATN lines of the GPIB (IEEE-STD-488) interface. Another IC (U28) provides the necessary output drive and input buffer amplifiers.

The major disadvantage of this software based interface is slow handshake speed. Since many of the logic functions are performed by the microprocessor software, it requires up to 3.5 milliseconds to transfer each data byte.

HIGH SPEED DISCREET IC INTERFACE

To overcome the limitations of a software driven interface, hardware designs using discreet IC's were developed. These designs allowed data to be tranfered at rates of over 12K bytes/sec. A block diagram of a typical hardware design for the GPIB interface of a high speed digital voltmeter (DVM) is shown in figure 2.

This interface circuit was designed to interface from a 6800 series microprocessor bus to the GPIB.

The interface is controlled by its own algorithmic state machine (ASM) which handles all interface commands and allows the GPIB to operate independent of microprocessor control.

The ASM is a 256 by 8 bit machine with a microcycle time of 250 nanoseconds. The circuitry consists of the ASM Qualifier Multiplexer, the Qualifier Storage and Jump Logic, the ASM Program Memory, the ASM Address Register and the ASM Address Decoder.

The GPIB ATN (Attention) line determines how the messages on the Data I/O lines are interpreted. When ATN is low, the bytes sent over the bus are intended for the GPIB board. When ATN is high, the bytes are intended for the microprocessor. In order to receive bytes from the controller, the GPIB board must have been made a listener while ATN was low. The controller does this by sending the DVM's listen address on the Data I/O bus. A comparison is made by the ASM with the device address switches on the DVM. If a match occurs, the listen flip-flop in the GPIB Status Storage is set by the ASM.

If the GPIB board is in the listen state and ATN is high, the ASM will handshake any byte made available over the GPIB. The GPIB board will then send an interrupt to the microprocessor, indicating that a byte is ready for the microprocessor.

When ATN goes low, the GPIB board responds within 200 nanoseconds. This is accomplished by having ATN reset the four control lines: Not Ready for Data (NRFD), Data Valid (DAV), No Data Accepted (NDAC) and attention latch (ATNL). This prevents the controller from sending data until the ASM program has a chance to execute the attention routine. The ASM program then starts the handshaking routine.

If, with ATN low, the ASM recognizes a byte from the controller as being its talk address, the talk flip-flop is set and the ASM handshakes any other interface commands. The microprocessor will recognize the talk state and will take readings as programmed. The data is passed on the microprocessor data bus and stored in the GPIB Data Output Latches. The microprocessor then sets the Next Byte Available (NBA) flip-flop indicating that a data byte is ready. After the ASM outputs the byte, it resets the NBA flip-flop which signals the microprocessor that it can load another data byte.

The GPIB Address Switch Read Buffer is used to provide a front panel display of the address set on the rear panel address switches.

Hardware interfaces of this type offer a significant improvement in data rate. Although relatively expensive to build, discreet hardware designs using high speed logic devices can offer state-of-the-art handshake speeds.

LSI INTERFACE DESIGN USING COMMERCIAL INTERFACE CHIPS

As the GPIB (IEEE-STD-488) interface became popular, the demand for packaged interface designs was met by the semiconductor manufacturers in the form of standard "off-the-shelf" LSI interface circuits. Table 1 lists some of the interface circuits presently available.

Table 1 - Typical commercial LSI circuits providing IEEE-STD-488 interface in single or multiple DIP packages.

Manufacturer	Part Number
(1) Fairchild	94LS488
(2) Intel	8291/8292
(3) Motorola	MC68488
(4) Signetics/Phillips	HEF4738V
(5) Texas-Instruments	9914A

The availability of off-the-shelf LSI circuit designs have both improved the performance and reduced the costs of GPIB interfaces. They have not, however, created a standard performance level for the GPIB interface among equipment manufacturers. One reason for this is that some of the LSI designs have design bugs or "idiosyncrasies" that must be compensated or corrected in external hardware or software designs. The designer's approach in implementing these LSI circuits can significantly change the way an instrument will perform on the GPIB. This is especially true of designs using the 68488 and 8291 type LSI devices.

68488 LSI BASED INTERFACE

One of the first GPIB interface circuits to be produced in LSI was the Motorola 68488. This device offers better performance than software type designs and lower costs than discreet IC designs. However, it has certain operational "idiosyncrasies" that can affect the performance of an instrument when used on the GPIB. How the instrument designer compensates for these "bugs" directly affects the ease with which the interface can be used on the GPIB. These idiosyncrasies include:

(1) EOI line (end or identify) on the GPIB cannot be reset under software control. Once this line has been set, the instrument must output the associated data byte.

(2) Documentation does not indicate the need for a pull-up resistor on the SRQ line. Without this resistor, the noise on the line may cause erroneous SRQ conditions.

(3) Data byte "in action" by the 68488 must be transmitted over the GPIB or overwritten. The 68488 will not allow the byte in process to be killed.

Unless the interface and instrument designers using the 68488 recognize and correct for the above weaknesses, they can adversely affect the bus operation of the instrument. While the problems associated with unwanted SRQ conditions are apparent, the EOI and "byte-in-action" problems can be more subtle. One example of the bus problems that can occur due to the inability to reset the EOI line is illustrated by the following sequence.

1) The instrument designer has used the EOI as an output terminator.

2) The instrument's microprocessor is transferring data to the 68488 for output to the GPIB.

3) Due to an SRQ elsewhere in the system, the final data byte and it's EOI terminator are not transmitted.

4) After servicing the SRQ, the system controller reprograms the instrument to another function and requests a reading.

5) The instrument's microprocessor "overwrites" the data byte in the 68488 with the first byte of the new reading.

6) The 68488 outputs the new byte plus the previously set EOI.

7) The controller terminates the measurement transmission upon sensing the EOI and indicates an invalid measurement.

8) Depending on when the SRQ is set, the fault may appear to be a random instrument (or system) failure.

While the "byte-in-action" problem may also appear to be random, it is usually associated with a reprogramming of a measurement instrument. If the instrument's software design allows the microprocessor to write to the 68488 whenever the instrument is taking readings (whether addressed as a talker or not), the following sequence may occur.

(1) The instrument takes a reading and transfers sequencial bytes of the reading to the 68488.

(2) The system GPIB controller addresses the instrument as a listener and tansfers new programming information.

(3) The GPIB controller addresses the unit as a talker. This triggers the unit to take a new reading.

(4) The 68488 handshakes out the previously stored data byte from the old reading.

(5) The microprocessor outputs the new measurement after the instrument has finished it's measurement cycle.

(6) The GPIB controller is confused by the "extra" byte and signals an erroneous reading.

The solution to the noisy SRQ is the simple addition of a pull-up resistor between the SRQ line (pin 23 on 68488) and the +5 volt supply. The EOI problem is more difficult to solve and generally results in the designer using the EOI as an input sense only. Other terminators such as carriage return and line feed are used to indicate the end of measurement data.

At least three methods have been used by designers to overcome the "byte-in-action" errors. One method is to inhibit the microprocessor from writing data into the 68488 until after the unit has been addressed as a talker by the GPIB controller. This eliminates the possibility of an erroneous byte on the GPIB output but requires the correction to be made in the operating firmware of the instrument.

A second method that has been used is for the microprocessor to immediately overwrite a "space" character into the 68488 whenever the unit is addressed as talker by the GPIB controller. This gives unwanted "space" characters on the GPIB and may cause extra effort for the system software designer. This extra "space" is especially difficult to accommodate when using high level system languages such as ATLAS.

A third method is a hardware circuit to prevent the 68488 from handshaking data onto the GPIB until new measurement data is available from the microprocessor. Racal-Dana has chosen to use the hardware solution.

Figure 3 shows a design using the 68488. This Racal-Dana design contains additional circuitry to compensate for the chip's idiosyncrasies.

The IEEE-488 interface is centered around the 68488. The other interface hardware includes bi-directional buffer/drivers; the serial poll disable decoder; the address switch buffer; and the GPIB output holdoff circuit.

The 68488 handshakes most in-coming interface messages from the controller and acts upon them without disturbing the uP. If and when an incoming message or data byte requires a response from the uP, the 68488 sends an interrupt request IRQ to the uP. The uP then examines the 68488 internal registers to release the IRQ and to determine the cause of the interrupt.

The GPIB "Output Holdoff Circuit" was added between pin 18 of the 68488 and transceiver pin 7 to solve the "byte-in-action" problem.

When the GPIB controller addresses the instrument as a listener and transmits a new programming instruction, the RFD line from the 68488 is disconnected from the buffer/driver and pulled to ground. This makes the 68488 believe the GPIB system is not ready for data. After the instrument has completed the next reading and the microprocessor has overwritten the "byte-in-action", this line is reconnected to the GPIB via the buffer/driver and normal handshakes are resumed.

This design includes the SRQ pull-up resistor (R93) and uses the EOI as an input only. When multiple readings are transmitted to the GPIB from internal memory, they are separated by a comma and the block of data is terminated by carriage return and line feed characters.

Although the 68488 has the idiosyncrasies discussed above, it has the major advantage of being a second source component. This ability to procure from multiple vendors may outweigh the technical problems that must be considered during the design effort.

TEXAS INSTRUMENTS 9914A LSI BASED INTERFACE

While the 68488 implements only the talker/listener GPIB capabilities, the 9914A contains talker, listener, and controller functions. The 9914A also supports DMA (Direct Memory Access) capability.

Although single sourced, the Texas Instrument's design overcomes the limitations of the 68488. Figure 4 diagrams a typical design using this chip with a DMA controller. All circuits outside the 9914A are for DMA except the GPIB buffer/drivers and the GPIB address switch buffer.

When using this LSI circuit without DMA, all that is required is the 9914A and the two GPIB transceiver circuits (buffer/drivers). Of course the GPIB address must also be established for the instrument's microprocessor. No other circuits are required unless DMA or controller functions are required.

INTEL 8291A/8292

Unlike the 9914A, the Intel design uses two chips to implement all of the GPIB functions. The 8291A provides talker/listener capabilities and the 8292 provides the controller function.

Although Racal-Dana has not used the Intel devices, several facts can be noted from the data provided by Intel.

It is very important to note that the 8291A is a improved version of the original 8291. The 8291 had several problems that have been corrected by the redesign. Older instrument designs using the original 8291 may exhibit both the EOI and "byte-in-action" problems of the 68488 design. The Intel handbook lists thirteen (13) changes between the 8291 and the 8291A. When using instruments containing the older 8291 chip, a review of these changes is recommended.

Like the 68488 and 9914A circuits, the 8291A/8292 devices are designed for use with microprocessor based circuits. They require Intel 8293 GPIB transceiver devices as support circuits.

SIGNETICS HEF 4738V AND FAICHILD 94LS488

These LSI circuits are not as popular as the preceding devices. They are designed for standalone hardware interfaces and do not easily interface to microprocessor designs.

The Signetics HEF 4738V requires use of two, 8 input, serial output converters for decoding the GPIB address switches.

The author has not had experience with these devices and is not aware of any possible bugs or idiosyncrasies.

SUMMARY

The use of LSI GPIB interface circuits can reduce the cost of implementing a GPIB interface. Figure 5 lists the common commercial devices available and key facts on each. Although lower in cost, they may have idiosyncrasies that affect operation. Discreet design may still offer state of the art in speed but is likely to be expensive.

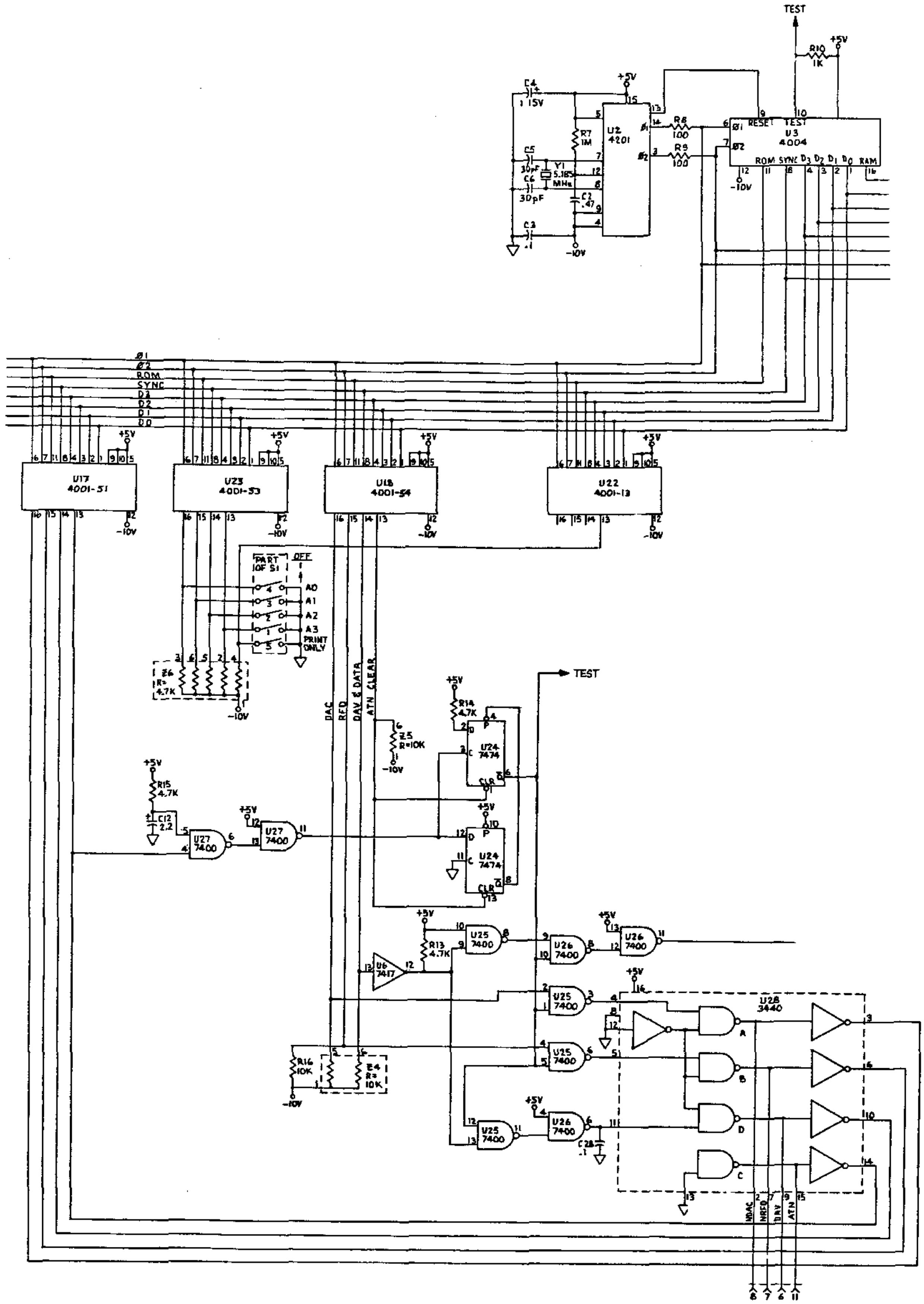

Figure 1 - GPIB (IEEE-Std-488) Interface designed with microprocessor software control.

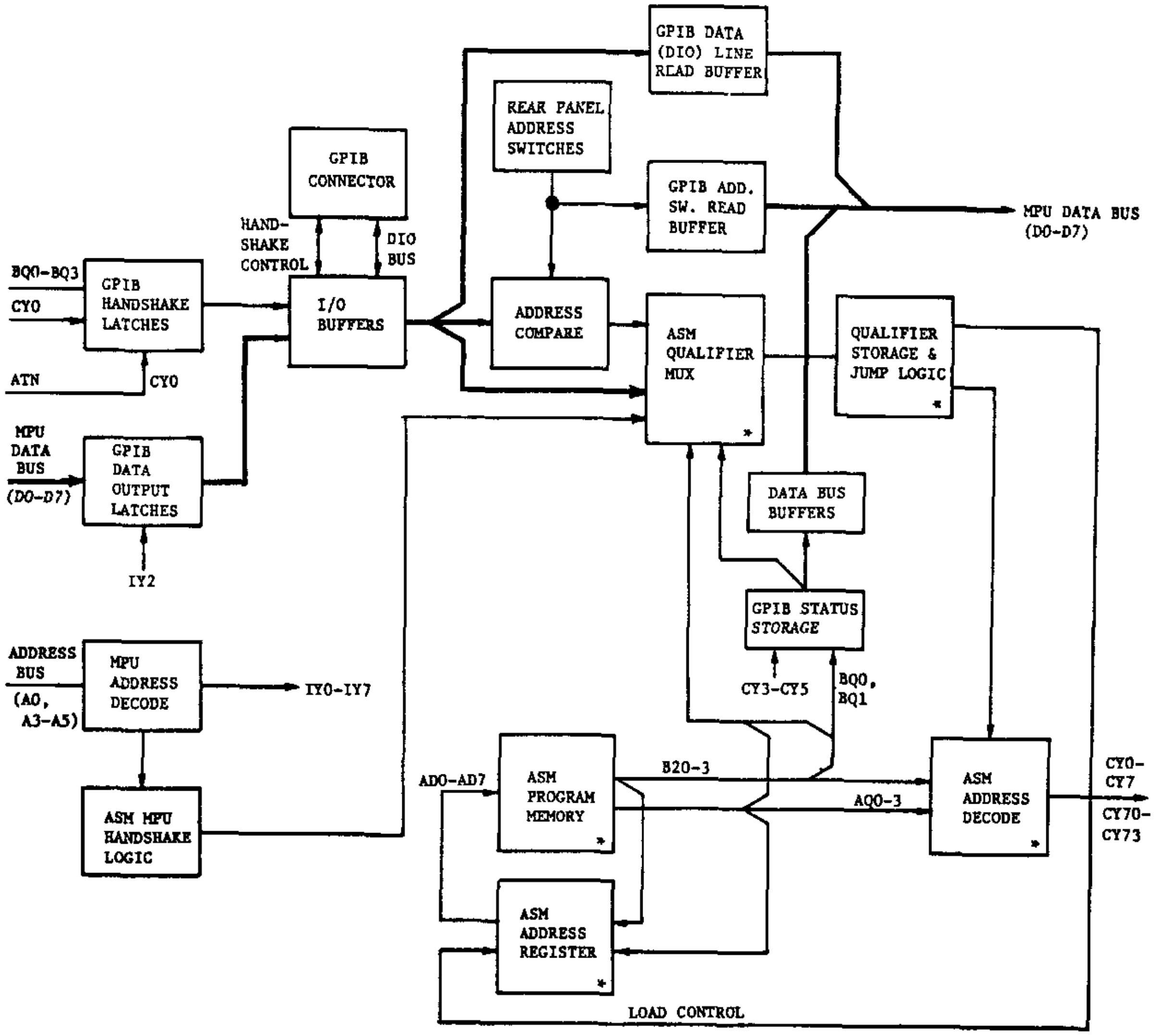

Figure 2 - GPIB (IEEE-Std-488) Interface designed with descreet IC's.

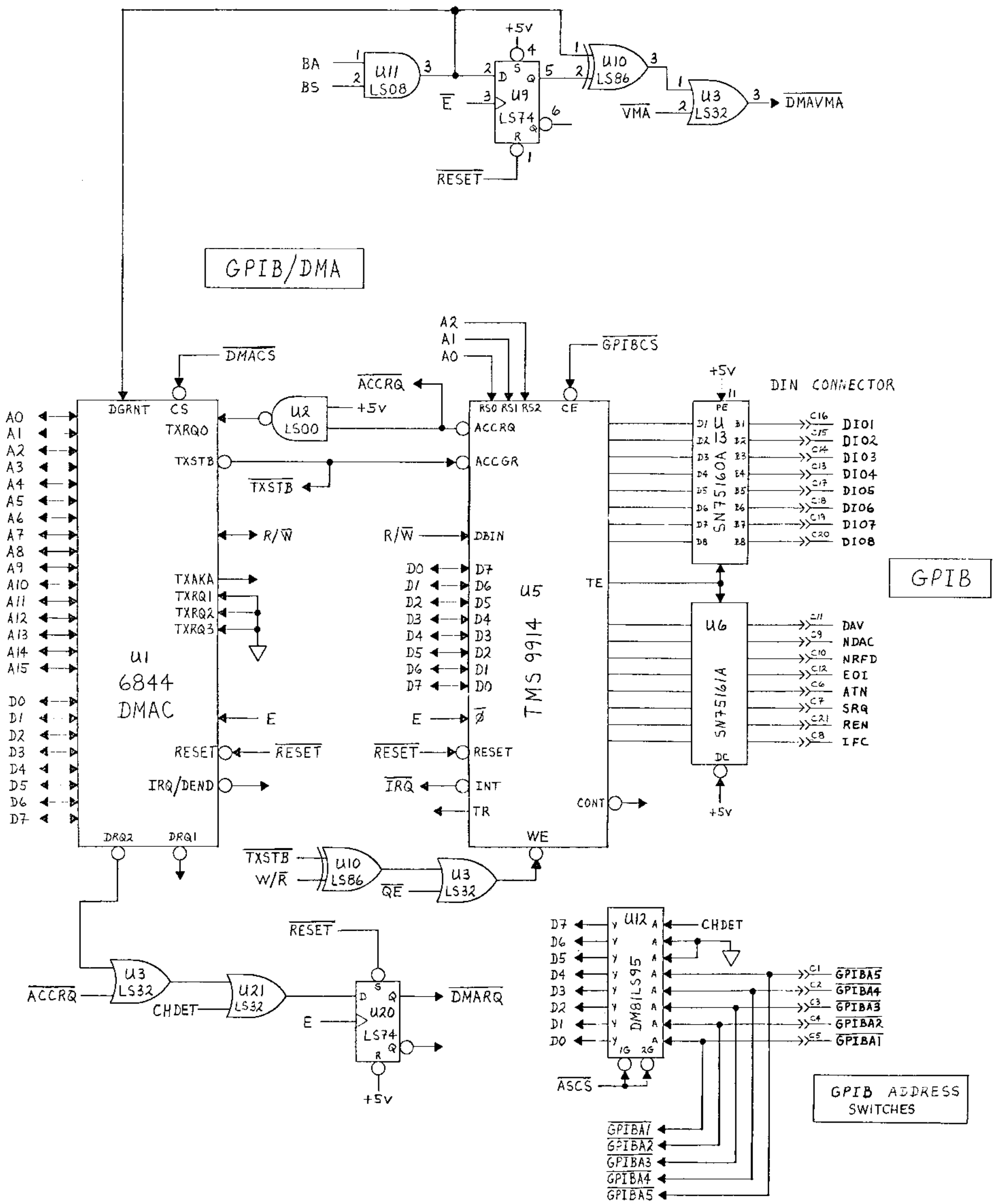

Figure 4 - GPIB (IEEE-Std-488) Interface using Texas Instruments
TMS 9914 LSI Interface Chip including capability for DMA.

MFG	P/N	DRIVERS REQUIRED	FUNCTIONS T	FUNCTIONS L	FUNCTIONS C	DMA SUPPORT	COMMENTS	OTHER CHIPS NEEDED
Motorola	68488	Yes	X	X		Yes	EOI, SRQ, Byte output idiosyncrosies. µP bus architecture. Second sourced.	GPIB Transceivers (2 ea.)
T.I.	9914A	Yes	X	X	X	Yes	Sole source. µP bus architecture.	GPIB Transceivers (2 ea.)
Fairchild	94LS488	No	X	X			Sole source. Stand-alone interface designs.	
Signetics/ Phillips	AEF-4738V	Yes	X	X	P	N/A	Sole source. Stand-alone interface designs.	Quad GPIB Transceivers (4 ea.) 8 input, serial output shift registers (2 ea.)
Intel	8291A	Yes	X	X		Yes	µP bus architecture. Major improvement eliminated bugs from 8291.	8293 GPIB Transceivers (2 ea.)
	8292	Yes			X	Yes		

Figure 5 - Standard LSI GPIB Interfaces

REAL-LIFE BUS PROBLEMS

Robert G. Irvine
Cal Poly University, Pomona

Kerry Kugler
General Dynamics/Pomona

POWER-ON vs. SDC vs. DLC

It is normally presumed that the Power-On (PON), Selected Device Clear (SDC), and Device Clear (DLC), commands place the instrument in the SAME cleared condition.

THIS IS NOT NECESSARILY TRUE.

INTERFACE CLEAR (IFC)

Sent, initially, by controller to clear all devices

Sent, subsequently, when

bus hangs up and the Selective Device Clear (SDC) and/or the Device Clear (DLC) commands cannot be sent.

The IFC command clears all setups in the instruments so it should only be sent as a last resort.

REMOTE ENABLE (REN)

The bus specification states subtly that the device will not become remote enabled until the REN and the MLA (listen address) of the device is sent.

This actually works as follows:

The REN bus command is sent by the controller in charge.

No devices on the bus become remote enabled.

As the listen address of each device is sent, that device becomes remote enabled.

HANDSHAKE LINE—NOT READY FOR DATA (NRFD) HELD TRUE

Start removing bus connectors until offending device is found.

WAVETEK INSTRUMENTS DO THINGS DIFFERENTLY

1. They formulate the NRFD line as the "inversion" of the NDAC line. This is in violation of the bus specification, but it works.

2. They have a 220 μs data command rate. This means that if a Wavetek instrument is on the bus, and addressed to listen, the bus rate has been reduced to 4.5 Kbytes/second.

UNTALK

The bus specification states that a present talker will UNTALK when the talk address of another device, OTHER TALK ADDRESS TO THIS DEVICE, has occurred.

THIS IS NOT NECESSARILY TRUE.

The untalk command should ALWAYS be sent before addressing another device to talk.

UNLISTEN-UNTALK vs. UNTALK-UNLISTEN

It usually matters in which order the two "UN" commands are sent.

If the UNLISTEN command is sent first, and the controller momentarily removes the ATN true between the two commands, a talker could send some data which would be lost on the now unlistened devices.

Therefore, to prevent this problem, ALWAYS SEND the UNTALK first. UNTALK-UNLISTEN.

LOCAL LOCKOUT (LLO)

Disables front panel controls to

Prevent knob twisters from changing settings.

Prevent operator from altering test to get part out.

INSTRUMENT RESOURCE TIME TO SET-UP COMMANDS

One would presume that the instrument would set-up immediately upon receipt of the set-up commands.

THIS IS NOT NECESSARILY TRUE.

They take varying amounts of time to respond.

Some of the older Wavetek instruments, with the 8008 microcomputer, took as long as 3 seconds to respond.

When Operating in Real Time, Problems Occur

The voltmeter, just set-up, does not respond until after the signal generator, previously set-up, has ceased to send its signal.

GROUP EXECUTE TRIGGER (GET)

One would thing that each device on the bus would respond immediately upon receiving the GET command.

THIS IS NOT NECESSARILY TRUE.

Thus, problems can occur in a real time test where the voltmeter must read at the same instant that the pulse generator sends its pulse.

1. It takes some time for each instrument to handshake the GET command.

2. Each device must then decode the command and respond.

There can be several microseconds between each device's response and another device.

MAXIMUM DATA TRANSFER RATE

Bus specification states that the maximum rate is 1 Mbyte/second

This rate is rarely achievable because the Slowest listener on the bus controls the data transfer rate.

With a bus analyzer on the bus, the rate can be as slow as 1 byte/second.

OVERRUN OF DATA FROM HIGH SPEED DISC MEMORY

Winchester disc drive--12,288 bytes/16.666 ms = 1.356 Mbyte/second approaching maximum data rate of bus.

If disc does not have track buffer, the data coming off of the disc can come too fast for the bus to handle and bus "overrun" occurs.

Solution

Use disc with track buffer so that data can be stored in the buffer and transferred over the bus at a slower rate.

ENCRYPTED BINARY

Some instruments, Hewlett-Packard as an example, send data bytes over the bus that are not ASCII characters.

Instead, they are status words, where each bit in the pattern means something. The instrument usually has two modes where, for example:

16 Bit Status Word Sent as a String of Ones and Zeros

	ZRO	ZRO	ONE	ONE	ZRO	ONE	ONE	ZRO	ZRO	ONE	ONE	ZRO	ONE	ONE	ONE	ZRO
DECIMAL	48	48	49	49	48	49	49	48	48	49	49	48	49	49	49	48
HEXIDECIMAL	30	30	31	31	30	31	31	30	30	31	31	30	31	31	31	30

or it can be sent as the "encrypted binary" bit pattern in two status bytes,

6 n , where 6 = 00110110 and n = 01101110.

END OF RECORD DELIMITERS

Different instruments demand particular "end of records."

Example: Record sent is	F	3	R	2	A	5		
Sample end of records required by instruments:	F	3	R	2	A	5	CR	
	F	3	R	2	A	5	LF	
	F	3	R	2	A	5	CR	LF
	F	3	R	2	A	5 EOI		
	F	3	R	2	A	5	CR EOI	
	F	3	R	2	A	5	LF EOI	
This one works in most cases	F	3	R	2	A	5	CR	LF EOI

AUTOMATED SYSTEMS AT THE STATE-OF-THE-ART

Loebe Julie
Session Developer
Julie Research Laboratories, Inc.
New York, NY

I have invited a distinguished panel of experts to present an overview of automated systems operating at the present-day limits of measurement performance and accuracy. The members of the panel will give a brief background of the subject, covering a broad range of measurements from DC to Microwave and from Electrical to zphysical and leaving time for a discussion of the automation/accuracy state-of-the-art for a wide variety of measurement disciplines.

Panelists: Mr. Bob Biller, Micro-Tel Corp.
Mr. Hank Gonzales, White Sands Missile Range
Mr. Milt Lichtenstein, Ballantine Labs
Dr. Arthur McCoubrey, National Bureau of Standards
Mr. Charles Weber, Grumman Aerospace

AUTOMATION AND ACCURACY-A POWERFUL DUAL THEME

In view of the fact that "Accuracy and Automation" is this year's Measurement Science Conference theme, it is hardly necessary to dwell on the importance of our session topic. Still the major implication of the twin theme deserves emphasis-- that there is a dual optimum in measurements to be achieved--an optimum in the exactness (accuracy) with which we perform our measurement functions and a second optimum (stemming from automation) in the cost and time effectiveness of our performance of these functions.

The enormous practical significance of this achievable maxi-max in measurement exactness and effectiveness has to do with the key role of our national measurement system in supporting a technologically sophisticated, multi-trillion dollar per year economy. The quality and cost-effectiveness of measurement support for our science, our manufacturing and our defense establishments to a considerable extent determines our national capability and productivity.[1][2]

Each measurement laboratory and every measurement scientist plays a vital part in the performance of the national measurement system. Maximizing the accuracy/cost-effectiveness of an individual laboratory thus not only benefits the productivity and profitability of the part but also makes an important contribution to the capability of the whole.

ACCURACY YES-ACCURACY NO
AUTOMATION YES-AUTOMATION NO

Having affirmed the theme, let me now quarrel with it, at least a little. Neither accuracy nor automation deserve special interest unless they actually deliver the practical benefits to the measurement function that managers and metrologists have a right to expect, i.e.-better and more useful measurements (because they are more exact), and better and more useful measurements (because they are faster, less labor intensive, more productive or more reliable by virtue of being automated). The desireability of increased accuracy/automation, whether to the individual laboratory or to the national measurement system, thus depends not on arcane theoretical or crass marketing arguments but on extremely careful practical evaluations of real benefits actually obtained in the real world. Out of such evaluation comes the determination of where the accuracy and automation (cost-effectiveness) optimum--the maxi-max benefit-- is obtained.

With careful evaluation the benefit potential in "accuracy and automation" is enormous. In fact, in the modern measurement laboratory, effective and accurate automation is the key to economic survival, since it represents "the only way to greatly improve laboratory cost-effectiveness while not degrading measurement quality."

AUTOMATION VERSUS AUTOMATEABILITY

Unfortunately, the term automation is applied to too many things, of too many sizes and scales, to be very meaningful. A miniature digital watch, a test instrument with built-in microprocessor and a rack-size computerized test system complete with all system interfaces and including all operating and application software are all referred to by the same catch-all word "automated".

While the words automation and automatic have the same root, automation has by far the broader meaning:

automatic--"made so that certain parts act in a desired manner at a certain time"

automation--"automatically controlled operation of an apparatus, process or system by mechanical or electronic devices that take the place of human operators"

Manual instruments have been made increasingly automatic by the addition, first of relay controls , later of solid state switches and logic circuitry and now of microprocessor circuitry; these additions provided data logging and remote programming capability, to which the microprocessor has added local number-crunching capability.

While these additions have made instruments more automatic and more automateable (i.e.-having a greater adaptability to automation), the automatic instruments themselves fall far short of providing the major benefits implied by the word automation--a great reduction in the dependence of the measurement process on human operator labor cost, time, training and experience. The new automatic and automateable instrument by itself is, in fact, a much more bewildering array of push-buttons and operator controls than its manual predecessors, and requires an operator of even higher training and skill level than before!

The manifold benefits (and, unfortunately, the equally manifold problems) of automation arrive when automatic instruments are first collected into a system configuration, then connected via an interface configuration to a computer/peripherals configuration, and finally integrated to a dual software configuration comprising both operating system and applications software.

To reap the enormous potential benefits while avoiding the problems of automation, requires either extraordinary luck or considerable engineering skill. At each of the five major levels of the system configuration design process it is essential to make an optimum configuration choice.It is unfortunately true that, in the real world, the overall system is only as strong as its weakest link. The statistical odds against designing an optimum or near optimum system, assuming a 50% chance of making on optimum choice at each of the five configuration levels, are thirty two-to-one!

Notwithstanding the high risk of failure in attempting a highly successful automated system design, the benefits of an optimum design, when achieved, make the risk well worth while. In my experience and, I am sure, that of the members of the panel, productivity gains from accurate measurement automation are large, operator costs are substantially reduced, operator training requirements more nearly match the skill and experience levels now available, and measurement quality and accuracy are maintained without degradation while measurement cost-effectiveness is substantially increased.

THE MANY FACETS OF "ACCURACY"-SPECIFYING "ACCURACY" ACCURATELY

If a measurement or calibration involved solely a single point comparison of two items, for example of a resistor under test to a Thomas type resistance standard, then the concept of accuracy would be single-faceted. But if the measurement, more realistically, is at more than one point--for example at several temperatures, and at several levels of voltage, and at several frequencies, and for a decade box at sixty different levels of resistance, then the concept of accuracy becomes multi-faceted.

Obviously, except in an unusually simple case, it is unacceptable to specify accuracy at only a single point. In order to specify "accuracy" accurately, all of the facets of accuracy, over the full performance range of the item under test, all of the levels , frequencies, sensitivities,and resolutions must be covered.

"ACCURACY"-THE CALIBRATOR INSTRUMENT

Configuring "accurate" automated systems requires selection of individual automatic or automateable instruments meeting uniquely high accuracy requirements. Fortunately our measurement industry has long recognized the need for and has developed a suitably high accuracy class of instruments, called calibrators, to be used as the (instrument) standards against which all other test instruments are periodically compared. These calibrators are designed to provide substantial (multi-faceted) accuracy safety factors when used to calibrate other test instruments--they are designed with wider ranges of amplitude and frequency, with better sensitivities and resolutions and with 4 to 10 times better accuracies over their broadened operating ranges.

The manual calibrator instrument has a long and honored tradition in the highest echelons of our measurement system-the standards and calibration laboratories. Accurate manual measurement and calibration would have been impossible without the development of the manual calibrator instrument-- by the smae token, accurate measurement and calibration automation is impossible without the accurate automatic calibrator.

There has been an unfortunate tendency in instrument specsmanship to downgrade the special word calibrator to be equivalent to the general word tester--leaving us with two words to describe general test instruments (of a wide variety of accuracy classes) and none to describe the specially designed and specially accurate calibrator instruments created as state-of-the-art reference standard instruments.

With the substitution of a motley array of test instruments for accurate calibrators has come a degradation in the concept of calibration itself. Because these test instruments lack the full range of performance of calibrators--i.e. amplitude and frequency range, sensitivity and resolution--the specification of accuracy has been treated as though accuracy was, as it is not, single-faceted. This has led to the substitution of single-value tests for over-the-scale calibrations, single-frequency tests for multiple-frequency calibrations, single-range tests for multi-range calibrations and, in sum, a redefinition of the overall calibration process so that it reflects not an accurate picture of the performance of the unit under test, but of the design limitations of the limited performance substitute calibrator.

In the interest of clarity, and in order that the words calibrator, calibration and calibration laboratory continue to have significant meaning, it is essential that the special name calibrator continue, as in the past, to mean those <u>accurate</u> (instrument) standards against which all other test instruments are compared.

Automation at high accuracy, the subject of this conference and this session, is at least theoretically achievable once automatic or automateable instruments of the calibrator accuracy class have been designed.

WHAT IS THE OPTIMUM CONFIGURATION OF CALIBRATOR INSTRUMENTS?

Measurement laboratories have had a quarter century of experience at selecting optimum configurations of calibrator instruments to support accurate manual measurements. By far the most successful method permits a measurement or calibration laboratory with only two or three dozen carefully chosen high-performance calibrator instruments-- to support thousands of models of test instruments of forty or fifty totally dissimilar classes and at whatever accuracy level is necessary.

By contrast with this extremely efficient configuration strategy, alternate configuration methods--using "shop queen" test instrument "standards" instead of calibrators, or using a variety of different narrow-range, special function testers instead of one set of wide-range, versatile, full-accuracy, general function calibrators--have proven completely impractical and,in the long run, enormously costly.

Too many recent attempts at automated measurement system configuration ignore the configuration lessons of our manual measurement and calibration history. The successfully proven configurations of versatile, full-performance and full accuracy calibrator instruments have not been used, while extensive use has been made of the successsfully disproven configurations of limited performance, medium accuracy and excessively specialized test instruments. The configuartion strategy of using instruments of performance has been even less successful in automated measurement system design than in manual. Not only does it obvioiusly fail to achieve "accuracy and automation" but it has failed to produce the expected automation benefits even as a limited performance backup capability in a measurement or calibration laboratory environment. In sum, to acheive optimum automation benefits, choose a small configuration of high performance versatile calibrator instruments.

BRIEF OVERVIEW OF "ACCURACY AND AUTOMATION" FROM DC TO 10 MHZ

Our panel's overview of accuracy and automation covers an enormous range-- from DC to Microwave and from Electrical to Physical. Part of this range, covering accurate measurement and calibration from DC to 10 Mhz, is of major interest, representing as much as 40% of the total of electrical and physical workload.

Systems operating in this range at the National Bureau of Standards, are to be described by Dr. McCoubrey. There is also published work by Julie Research Laboratories on automated systems operating in this range.[3],[4],[5]

There have been and are some systems operating in this extremely important portion of the electrical spectrum--HP9213, Fluke

Terminal 10, Rotek PAMC50, Valhalla 227000, Fluke 5100, Fluke 7405A. The first two are apparently no longer in production, while the remaining four are advertised as systems for limited accuracy applications.

"ACCURACY AND AUTOMATION" BENEFITS-SUMMARY

Data that the author is familiar with indicates that extraordinary benefits have been realized over substantial parts of the DC to Microwave and Electrical to Physical spectrum of measurements.

For example, in the DC to 10Mhz range, calibration labor is reduced (without any reduction or degradation of calibration accuracy, range, resolution or sensitivity) by an average of one hour per calibration.

The total incremental cost of automation (difference between the capital investment, maintenance, depreciation and software cost of the automated system and the manual system(s) it replaces) ranges from a maximum of $25 per day for a small laboratory to zero (or less than zero) for a medium-size or large laboratory.

The breakeven point for automation, at $25 per hour, occurs at an extraordinarily low workload density-- one calibration per day!

At workloads above one calibration per day the system returns a profit of $25 per calibration (or $62 per hour used) above its total incremental cost.

At full capability (16 calibrations per 8 hour shift) the system returns a theoretical profit above its total incremental cost of $375 per day.

Whether benefits of this magnitude from "accuracy and automation" are <u>really</u> achieveable has been the subject of a number of government agencies studies and evaluations.[6],[7] Following a recent survey and assessment by the Office of the Secretary of Defense,[8] a letter from Deputy Under Secretary of Defense Long to Senator Jackson describes responses to the OSD survey from users as follows:

"The responses reflected a clear consensus that the equipment had a high capability for calibration and measurement with great accuracy, was reliable, well designed and of quality construction, and offered the potential for an early return on investment if utilized frequently. One response indicated that a unit purchased in 1976 has had a 690% payback to date."

It appears safe to say that "Accuracy and Automation" is here to stay.

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ABSTRACT:

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...Electrical/Electronic instruments (73%)
(voltage, current, resistance, capcitance, and inductance)

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...Execution of consistant procedures, and making consistant judgements

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Although all of the above are directly or indirectly related to the costs of calibration the highlighted reason is the subject of this discussion. The effects of making consistant judgements could not have been so easily analyzed without the validation process which we use in the installation of automated processes.

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In the late 1970's WSMR studied the reliability of signal generators and found from a fitted Weibull distribution that the estimated reliability ranged from 45%to 62% for various models.(1,2,3) At this time automation was available to increase the capacity to double the calibration frequency. This increase in frequency theoretically would provide the improvement of reliability to our goal for this population. An extensive process validation test was performed with parallel testing on the automatic station and the manual station. This resulted in collection of data on in or out of tolerance judgement comparisons for the two methods of test. The measured value of reliability (proportion good) on reciept for calibration was found to be inaccurate. This inaccuracy equalled 15% of the judgements made. For models with the near 60% defective the expected error in the population proportion defective would total 9% of the total population. Since the error was commonly found to be an error of the first kind the excess costs associated with this are caused by over-calibration in two forms:

...the cost of trouble-shooting the current action and the unnecessary extra service

...and the costs associated with the needed extra calibrations indicated by the analysis of the reliability

This type of error produces the requirement to calibrate at a frequency which is greater than is necessary to achieve a selected reliability goal.

EXCESS COST COMPUTATION

Using the exponential distribution as a good approximation of the reliability of instruments submitted for calibration and: Given a constant failure rate and a time interval T (in years) we wish to investigate the effect of data accuracy on the computation of a service interval. Assuming a goal of .8 reliability and a constant failure rate lambda the required interval for calibration would be:

Solving $R = Ce^{-\lambda T}$ for T (C=.9559 outgoing quality)

$$T = -\frac{1}{\lambda}\log\frac{R}{C}$$

=-1/.2 log(.8/.9559)

= .38 Years = 141 days = req interval

These expressions will be used throughout this discussion to calculate service intervals for different levels of reliability.

If we make different assumptions on the accuracy of the reliability data, we can derive the following:

If the data accuracy is .85

then good = in-tolerance

bad = out-of-tolerance

Currect 'good' instruments = (.8)(.85)=.68

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then current reliability = .68 + .03 at the time of receipt for calibration.

Therefore for .85 data accuracy the instruments supported are being under calibrated.

Service Costs due to this Under Calibration

cal/yr 162 days = 2.25

cal/yr 141 days = 2.58

delta = .33 cal/year under calibration

If the outgoing quality level of calibration is .9559 and you assume .8 reliability with .85 accuracy with an error of the second kind the current true reliability is .71. Therefore, .09 of the good instruments are actually defective (ignoring errors of the first kind). If we eliminate this .09 by increased calibration and use the approximation of 1/2 of the .09 proportion defective as the average proportion defective in the hands of the users the savings could be computed:

INVENTORY COST

(.09)(1/2)(.9559)(25,000)($1741/inst)=$1,872,210

ADDED SERVICE COSTS

(.33)(25000)(1.6)(34.65) = $457,380

TRUE SAVINGS

Inventory costs	$1,872,210
Added service cost	-457,380
	$1,414,830

The following chart is based on these assumptions:

1) Reliability goal for the inventory; .8
2) Time interval established for inventory; 141 days
3) Cost of service; $34.65/hr
4) Total units in the population; 25,000
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6) Error in data is equally likely to affect % defective as % in tolerance (normal distribution)
7) Laboratory output quality at T=0; .9559

NET SAVINGS IN CORRECTION OF DATA ERRORS

DATA ACCURACY	COMP REL	SPEC INT	COMP INT	DELTA CAL/YR	NET SAVINGS
50%	50%	141	205	-.79	$5,132,578
60	56	141	192	-.69	4,036,324
65	59	141	187	-.63	3,497,906
70	62	141	181	-.56	2,963,514
75	65	141	175	-.49	2,441,210
80	68	141	169	-.42	1,913,832
85	71	141	162	-.33	1,290,090
90	74	141	156	-.24	915,145
95	77	141	149	-.13	443,425
97	78	141	146	-.08	263,562

COSTS OF ERRORS OF THE FIRST KIND

In considering the costs related to errors of the first kind (rejecting a good instrument), the condition that we found to be the most common we must consider the two elements of cost mentioned previously.

If we look at defectives which are, in fact, in tolerance at a mesured reliability of .8

.2 defective (.85 data accuracy)

.03 the proportion good (of the population) which is in error called defectives.

The service costs which are unnecessary = (.03)(1.6hr/cal)(25,000)(2.58cal/yr) = $3096. Which at this level of reliability is negligible but becomes significant when the proportion of defectives is high.

However, the excess service costs for the indicated increased calibration frequency is significant.

T = log(.77/.9559)/(-.23) = .40

The excess costs are then:

(2.34)(25,000)(1.6)($34.65)(.06) = $194,594

CONCLUSIONS

Although the data presented in this discussion have not been exact the generalization of the order and sensitivities of cost to variations of error should be representative of the situation at WSMR.

It is concluded that errors of the first kind produce insignificant excess costs for the added testing during an action. However if the calibration interval is established using this faulty data excess service costs will be suffered, for a greater number than necessary calibrations will be performed.

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IMPLEMENTATION OF AN IEEE-488 GPIB

AUTOMATED OSCILLOSCOPE CALIBRATION SYSTEM

Milton J. Lichtenstein
Vice President
Marketing Department
Ballantine Laboratories, Inc.
Boonton, New Jersey U.S.A.

ABSTRACT

One of the most ubiquitous of electronic test instruments in use today is the cathode-ray oscilloscope. The quantities of these units are exceeded only by small multimeters. As a complex instrument, verification of performance is generally performed one to four times per year in well directed quality assurance programs. Since checks made with manual test equipment, such as amplitude calibrators and time mark generators, can require from two hours to a full day, and require high skill level technicians, the cost and time spent to verify, calibrate and maintain an oscilloscope inventory of as few as 40 instruments can be a substantial overhead expense. Computer controlled oscilloscope calibration systems are now available to address such testing and to provide quality controlled checks, at high speed with a most salutary effect on cost reduction.

INTRODUCTION

Most oscilloscopes are equipped with some simple front panel available calibration signal allowing minimal checks of wave shape performance, timing, and more usually, adjustment of probe compensation. These internally provided signals cannot be used for general performance certification.

Standard bench instrumentation such as square wave generators, oscillators, frequency counters, time mark generators and pulse generators can be adapted for more complete testing; but since they are general purpose, their operation requires manipulation and some computation to track with the oscilloscope's front panel range markings. For example, checking one vertical channel amplitude range calibration with a square wave source requires that the calibration signal be adjusted and monitored to give a trace the desired number of divisions on the CRT display for the range being tested. Any deviation of the trace from the exact number of divisions set constitutes the calibration error, but this deviation must be estimated visually and the percentage of deviation, or error, then calculated. Similar adjustments, reckoning, and computation occur for other scope functions such as time bases (fixed and delayed) and more.

The burden of testing with general purpose instruments was relieved commencing about ten years ago, with the introduction of dedicated oscilloscope calibrators which include the Ballantine 6125B and the Tektronix PG501/TG501. These units produce calibration signals to check all major oscilloscope functions and parameters. The Ballantine 6125B is a single cabinet instrument, while the Tektronix PG501 and TG501 are modular elements that plug into a required main frame and power source. Both instruments are designed with front panel controls that track amplitude and time ranges in the same sequences found on conventional modern day oscilloscopes, and reduce the need for much computation by reading deviation directly in percentage on a digital display. They also provide fast rise pulses to check vertical amplifier rise time, as well as other convenient outputs to verify trigger sensitivities and sync modes. Such instruments have increased the calibration technician's speed; but still require manual operation and data taking.

With the advent of the IEEE-488 bus, and bus compatible inexpensive controllers and micro-computers, automation of scope calibration became a natural and achievable step. The first step in this direction was the Ballantine 6125C-Option 60 (Figure 1) a bus interfaceable version of the manual 6125B. It provides full oscilloscope amplitude calibration capability from 10 microvolts to 220 volts using 10 Hz to 10 kHz flat topped square waves and dc of either polarity, with $\pm$ 10.00% deviation and accuracy of 0.25%. Its time source can cover scope ranges from 2 nsec to 50 sec intervals and provide 10, 5, 3 or 2 markers per sweep at an accuracy of $\pm$ 0.02% of setting. Again, deviation can be ranged $\pm$ 10.00%. A low cost frequency doubler can provide a 1 nsec interval capability.

The calibrator also provides a rise time and trigger output; pulses at repetition rates from 100 nsec to 1 sec (10 MHz to 1 Hz) with a rise time of better than 1 nsec into 50 ohms. Amplitude is adjustable 200 mV to 250 mV into 50 ohms. A filtered sine wave at power line frequency, adjustable from 0 to 1 volt peak to peak is available for sync mode and sensitivity testing.

Thus, all the elements for "automating" scope calibrations were in place, except for software. Ballantine now has developed software to run a complete turn key computer controlled system combining the 6125C-Option 60, a personal computer, a dual disk drive, and a printer, and provides this as the Ballantine COMPUTEST 4000A System (Figure 2). The system's structural concepts, and the objectives to be satisfied in its use will be discussed later.

AUTOMATED CALIBRATION

The decision basis for the level of automation the system design was to achieve, was based in good part on the following considerations.

The complexity and degree of sophistication of "automated" calibration can be categorized into four major levels:

(1) Straight forward setting of a series of calibration outputs from a prepared machine, or tape-read test routine, with comparison of tested accuracy against specification limits, usually accomplished automatically. Operator involvement requires choice and setting of range and function controls on the unit under test (UUT), read out of the UUT display, and feedback of results to the system.

(2) Control by computer of the calibration test settings in a pre-programmed sequence; automatic specification checking; storage and/or printout of the results. The operator still is involved in readout of the UUT and may have options to make adjustments in the UUT when failures occur. Some decision making is preferably left to the operator to maintain interest in performing the tests.

(3) Closed-loop calibration. Complete computer control of the calibrator. Application of the test signals to a programmable UUT with talk/listen capability. Operator involvement consists solely of connecting UUT to the system and commanding the calibration system to calibrate.

(4) Self-check capability within the UUT itself under internal microprocessor control. No external calibration system required. State of the art permits further extension to make the UUT self-adjust when an external accurate source is used.

The fundamental question "why automate" also needs to be addressed in launching any ATE design. Principally the needs eminate from the following requirements.

(a) Calibration, on a managed and timely basis is required for both the quality assurance that a company's products have been properly tested, and in many companies also because it is required by government or commercial contracts.

(b) Skilled calibration technicians are in short supply. Simple instruments provide no challenge to such technicians and repetitive calibration of large numbers of unsophisticated units can cause job disinterest.

(c) Certification and verification of instrument performance by manual methods usually requires more time than repair and recalibration, and uses high skill level personnel. Labor rates become costly and bear heavily on overhead budgets.

(d) Down-time for instrument verification or calibration reduces production and lab test efficiency while such departments await return of test equipment, with attendant added time and expense.

(e) The non-productive overhead costs represented by calibration (unless the business of the company is calibration services) requires that all means be employed that will reduce calibration time and required skill levels.

(f) The complexity of present day instruments requires much complex testing. Manual procedures are subject to human error. Automated systems provide the rigid quality control that insures all tests are fully performed, and in proper sequence.

(g) Manual recording of results is tedious, time consuming, expensive, and again error-prone. Typing transcriptions of manually logged results adds to expense and potential error. Storage of results wastes space and look-up time. Automated systems can perform accurate record keeping, type certificates, and store enormous banks of data on small disks.

Overall then, an automated calibration system should reduce throughput time; allow lesser skill levels to operate the system leaving the higher skilled technician more available for the more demanding jobs of instrument maintenance on the more technically challenging instruments that may require manual calibration; perform record analysis and storage, time the calibration process if needed, and printout calibration certificates. Optionally, it can provide the data base for record manipulation required in managing the calibration records, instrument recalibration scheduling, equipment location and general instrument inventory management.

SYSTEM DESCRIPTION

Ballantine chose, as the direction of the future of automated systems, to structure systems following the requisites of item (2) above.

The software is configured to be used by technicians and operators having no knowledge of programming. Since every calibration activity performs various levels of verification and calibration to meet specific company needs, calibration procedures should not be pre-prepared and "canned" for users by the system manufacturer. Much time would be wasted by the user in learning to modify and convert a canned program to his requirements, and presumes that programming proficiency is resident on the user's staff, which is often not the case.

The Ballantine COMPUTEST software allows a technician to structure as complex or simple a test procedure as needed by providing a fully menu oriented program that uses no programming jargon, presents clear graphics and tables for fill in, and prompts, and instructions. Neither the technician generating the procedure, or the operator who uses it requires any programming experience.

A block diagram of the Ballantine 4000A COMPUTEST System is illustrated in Figure 3. The computer chosen as the system controller is a reliable, inexpensive, personal computer made by Commodore Business Machines, and the entire system runs on the IEEE bus. The Ballantine COMPUTEST program is written mainly in BASIC, and being complex and in excess of the 32k bytes of RAM in the computer, it uses swapping techniques (virtual memory) to make the dual disk drive an extension of the system's main memory. The drive adds another 320k bytes of memory to the system. Optionally a 1 M byte drive can be substituted. The large capacity dual disk drive allows many test procedures and results to be written to disk without the need for frequent disk changes.

The COMPUTEST program also requires the operator to enter a password if he selects a "View/Edit" or "Delete" function. This protects the integrity of test procedures written to disks by disallowing modification of a test procedure by unauthorized personnel. The program also provides options to give a hard copy printout of the test procedure itself.

Additional functions in the program not shown here, include "Extra Checks" which allow insertion of tests not provided in the main or sub menus, and "Utilities" which latter provides instructions on formatting and initializing procedures and results disks, and preparation of back-up disks.

On loading the master program in Drive Ø, the main menu (Figure 4) is displayed. The operator can then chose to generate a new test procedure by selecting options from the left column and following screen instructions, or, if he seeks a procedure to calibrate a UUT the operator would enter from the right column the option to select procedures (Read data) already on file on the Drive 1 procedures disk. After a procedure is loaded the "procedures" (data) disk is replaced by a "results" disk.

To begin the calibration sequence the letter "C" (calibration) is entered, or if only one function of the calibration is desired "C3" or "C5" etc. can be typed.

The system will ask for identification of the scope (manufacturer, model, serial number) and operator's name, date, and how the results are to be stored. Let us assume the operator has chosen a procedure which has a "Functional Check" in its sequence to test the UUT's coupling. The "DC-GND-AC" check previously put on disk will be presented with the graphics and instructions shown in Figure 5. Since the system is intended for use by operators with lesser skills than the calibration technician who prepared the procedure, the operator is given this clear, easy to read display and instructions to insure correct settings of the UUT, and asked to enter the required data.

When an Amplitude or Time check is being made, a similar display instructs the operator to adjust the "Deviation" control on the 6125C until it is the proper number of divisions high (Amplitude check) or until time markers line up with vertical graticule lines (Time check). A following instruction tells him to press the keyboard space bar, at which entry the percentage error displayed on the 6125C is recorded, compared to the allowable error in the procedure, and "Pass" or Fail" flags appear. If the check is a "Fail", he is given an option to make adjustments and retest.

When the next test point in a check is to be made, the display flashes those UUT controls to be changed. At the end of a test sequence, the system totals all failures and gives further options to adjust and retest. If the option to log calibration time has been chosen at the start of the procedure, the time is recorded, and the operator has some final options to enter comments at the bottom of the certificate and to elect to print the system (6125C) specifications. Finally, print options can then be activated.

When generating a new test procedure, after chosing from the left side of the main menu and following sub menus as typed in Figures 6 and 7, the calibration technician simply answers questions and fills in tables. Before committing the procedure to a disk, it can be tried and corrected, as needed, with the View/Edit facility. The procedure when written to disk with the "W" function is then identified by instrument manufacturer, model, and procedure I.D.

The print "p" function allows printout of the calibration certificate (Figure 8), either for a just completed calibration, or for a unit which may have been stored on a results disk for months or years. In this function, the certificate can be viewed on the CRT screen only if no hard copy is needed.

The Ballantine 4000A System will verify and calibrate oscilloscopes with bandwidths up to 500 MHz. For calibration of state of the art scopes of 1 GHz or better capability, the Ballantine 4002A System using the Ballantine 6127A Programmable Oscilloscope Calibrator, can be used. The 6127A (Figure 9) has amplitude ranges similar to the 6125C-Opt.60, but provides timing signals from 500 psecs to 5 sec. It also provides a fast rise time pulses to 1 volt peak to peak with a better than 200 psec rise time into 50 ohms, and a low distortion pulse mode from 1 to 100 volt peak to peak, 1 kHz to 1 MHz. It has provisions for checking the accuracy of a UUT's internal calibration signal, and a current signal for checking current probes. The integrity of the 6127A is automatically checked on every power up or CLEAR command by an internal uP run program verifying all major operating functions including front panel, displays, and the unit's RAM. The 4002A System includes the 4020A COMPUTEST software package, which runs similar to the 4010A (6125C) program, and uses the same Commodore computer, disk drives and printer.

CONCLUSIONS

(1) Automated oscilloscope calibrations now are available as catalog items, fully configured for operation by personnel who are not required to be programmers.

(2) Such systems are highly cost effective. Where regular verification and calibration is required in scope inventories of 40 or more instruments.

(3) Such systems are highly flexible allowing preparation of user-tailored procedures and eliminates the necessity to use "canned" rigid and hard to change programs.

(4) Throughput can be increased by factors of 4 to 5 times that of manual methods.

(5) Automated systems provide better control of the quality of testing and accurate and faster record keeping and certificate hard copy.

(6) Skilled personnel can be freed for more challenging, satisfying, and complex work assignments.

It should be noted that considerable impetus to the development of automated and portable calibration systems was given by the U.S. Navy's Metrology Engineering Center, who for about 7 years have been setting the standards and specification requirements for the MECCA program (Modularly Equipped and Configured Calibration Analyzer) in conjunction with equipment purchased from commercial manufacturers. Suppliers to the Navy of programmable "MECCA" Oscilloscope Calibrators include Ballantine and Tektronix. Fluke Mfg. Company provides their 1720A as the "MECCA" Controller.

REFERENCES

(1) Instruction Manual, Ballantine System 4000A and 4002A Automated Oscilloscope Calibration Systems.

(2) Instruction Manuals, Ballantine 6125C-Opt.60 and 6127A Programmable Oscilloscope Calibrators.

(3) IEEE Standard 488-1978 Interface Bus.

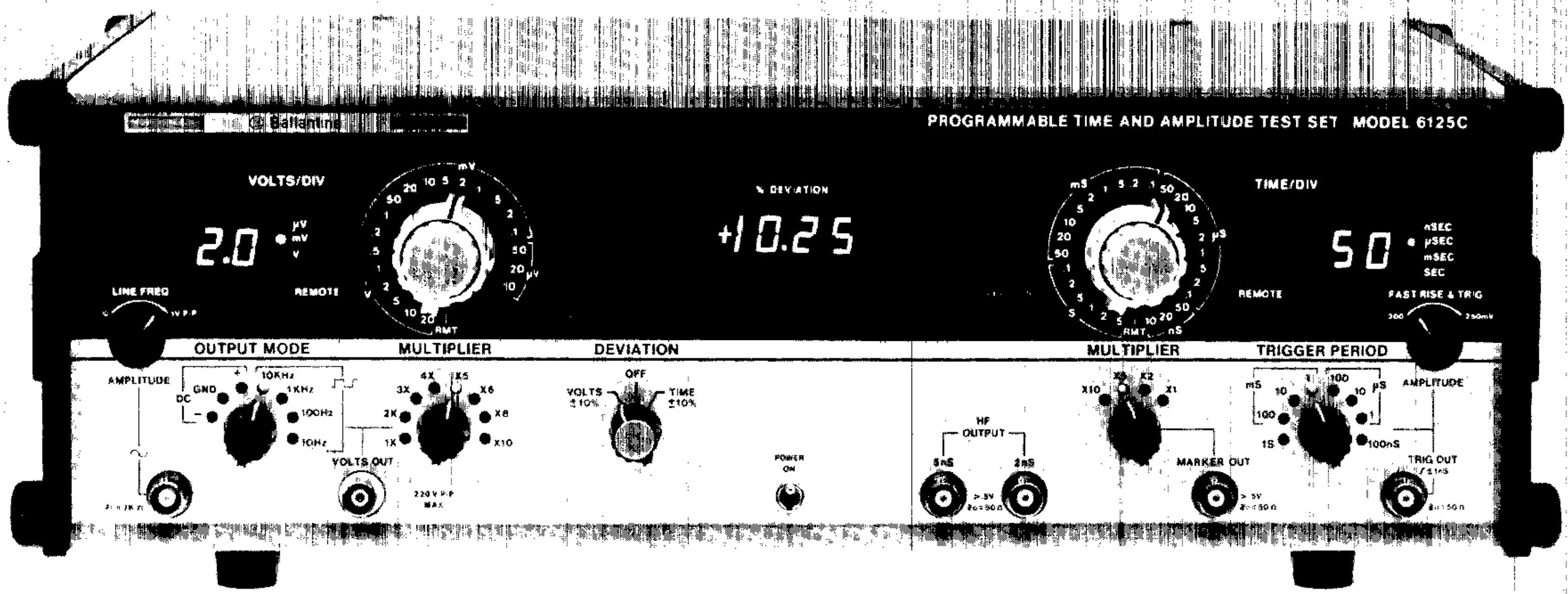

FIGURE 1. BALLANTINE 6125C–OPT.60

PROGRAMMABLE OSCILLOSCOPE CALIBRATOR

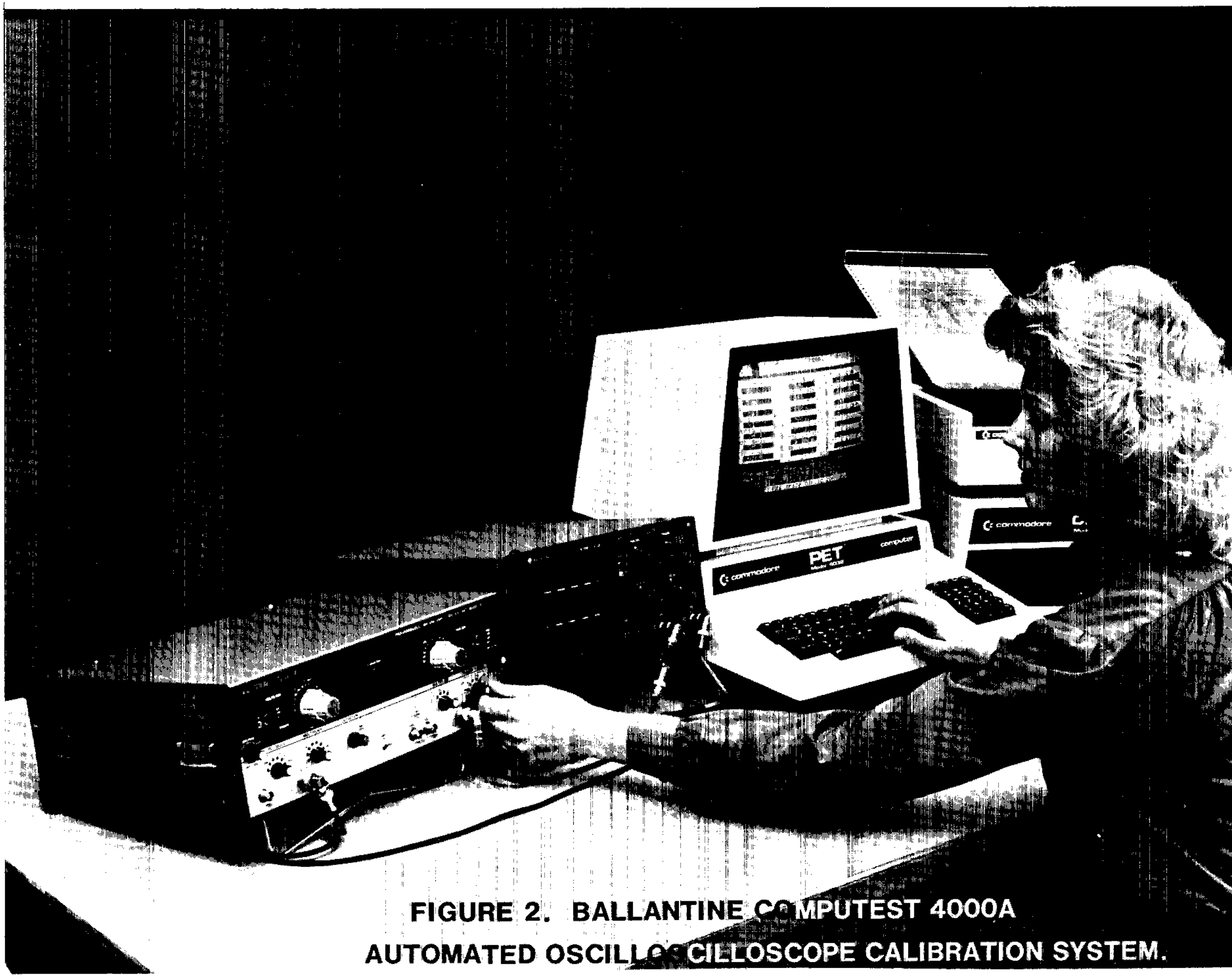

FIGURE 2. BALLANTINE COMPUTEST 4000A
AUTOMATED OSCILLOSCILLOSCOPE CALIBRATION SYSTEM.

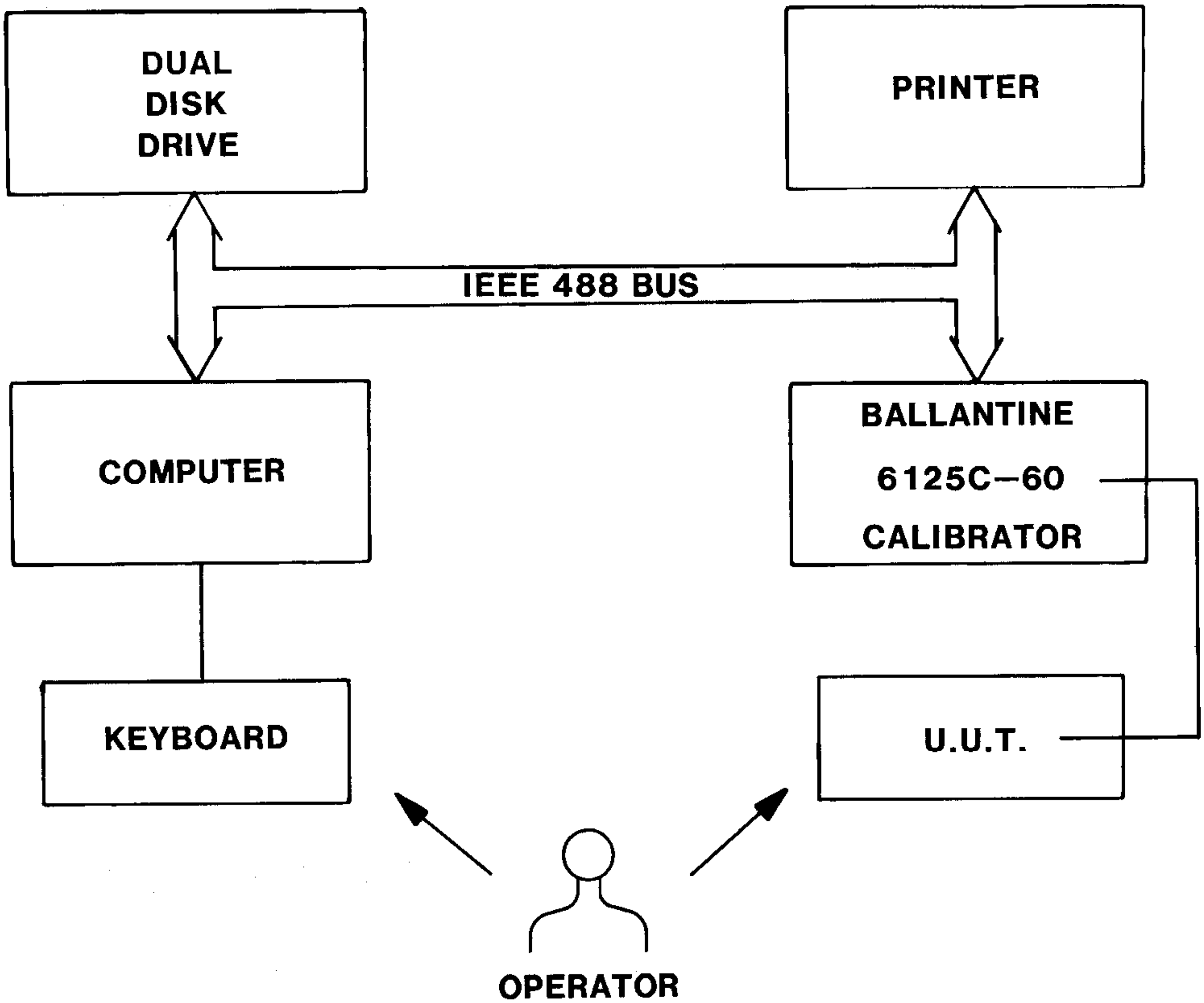

FIGURE 3. BALLANTINE 4000A
COMPUTEST AUTOMATIC CALIBRATION SYSTEM

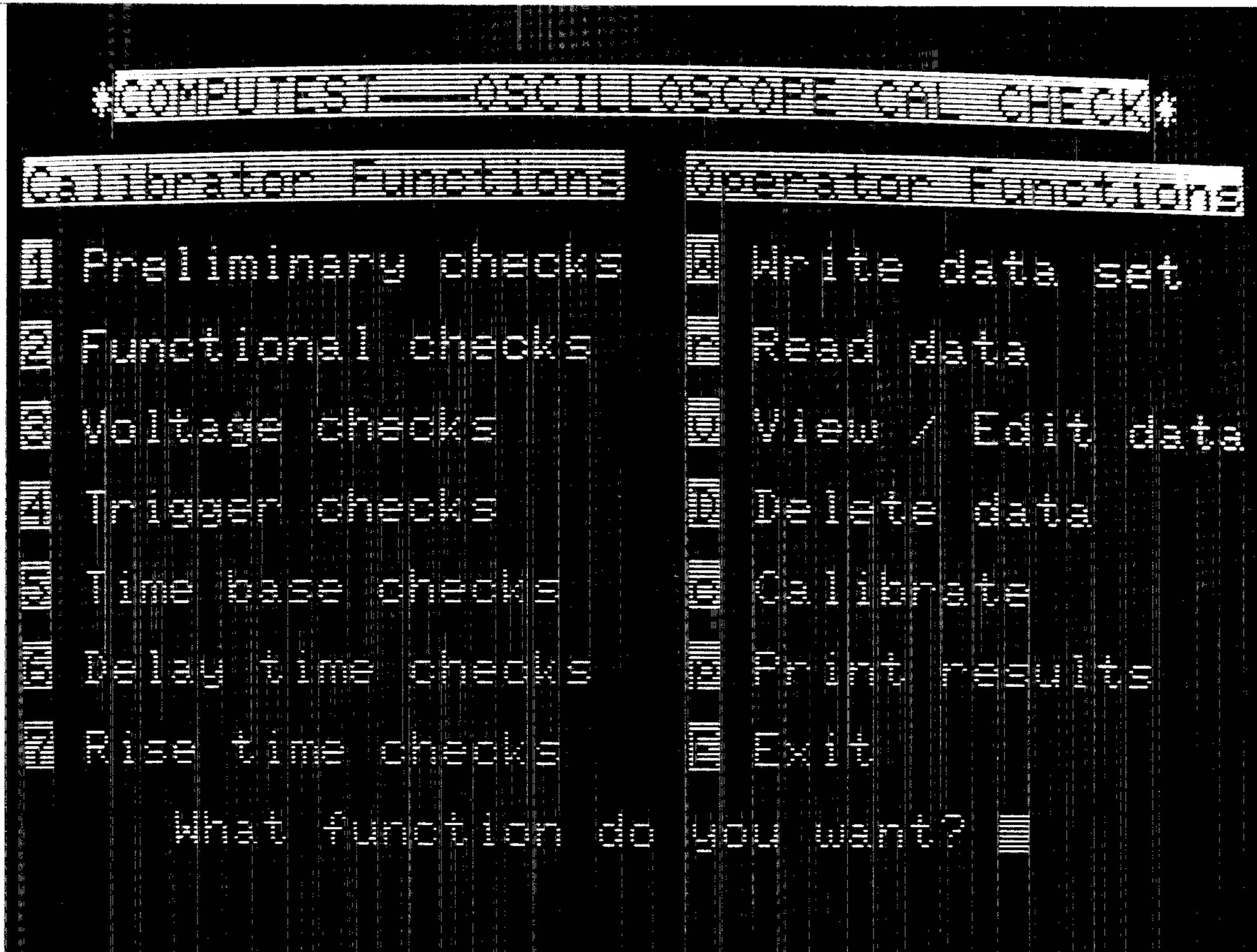

FIGURE 4. MAIN MENU — BALLANTINE 4000A SYSTEM

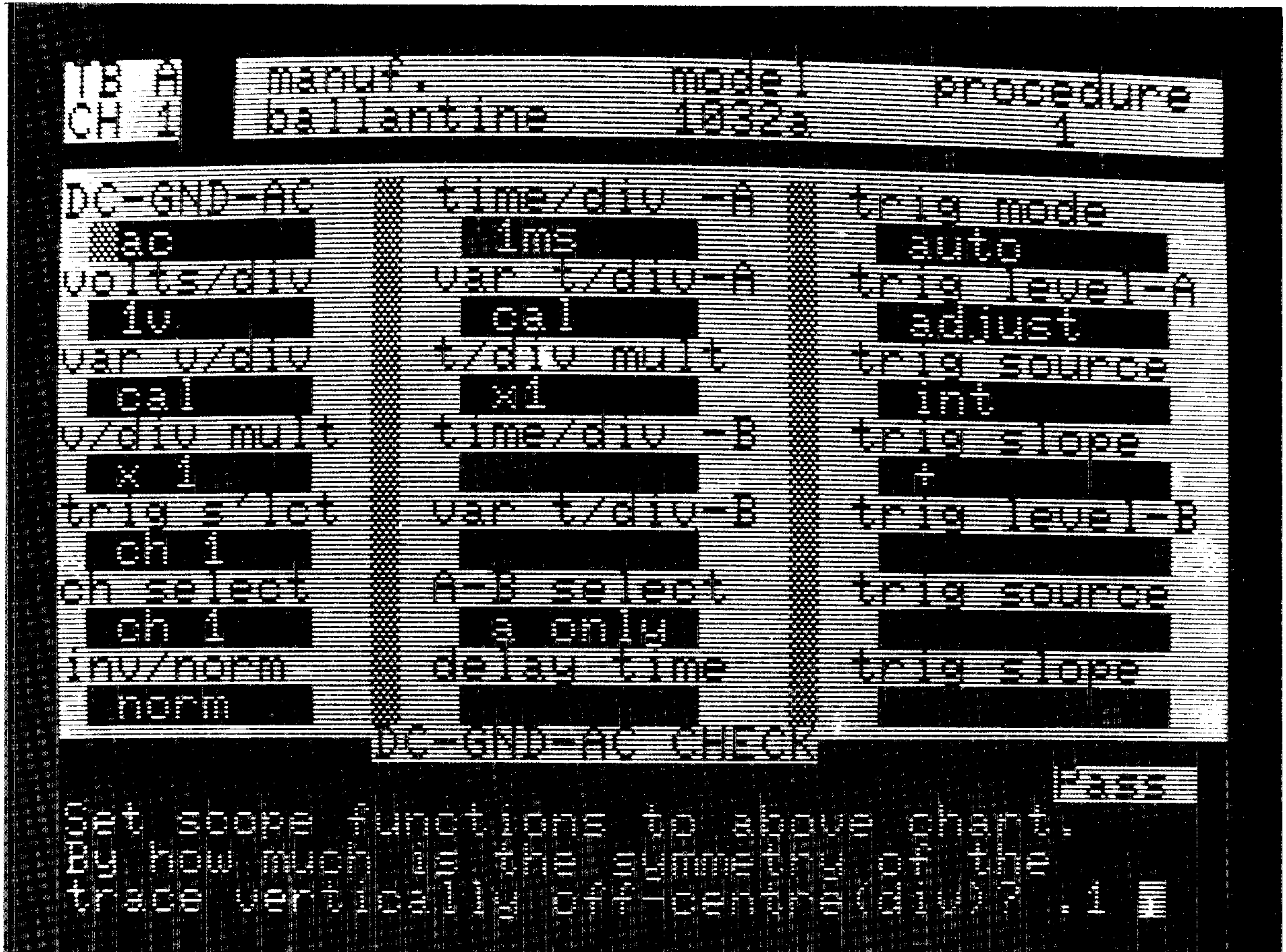

FIGURE 5. DC—GND—AC CHECK DISPLAY.

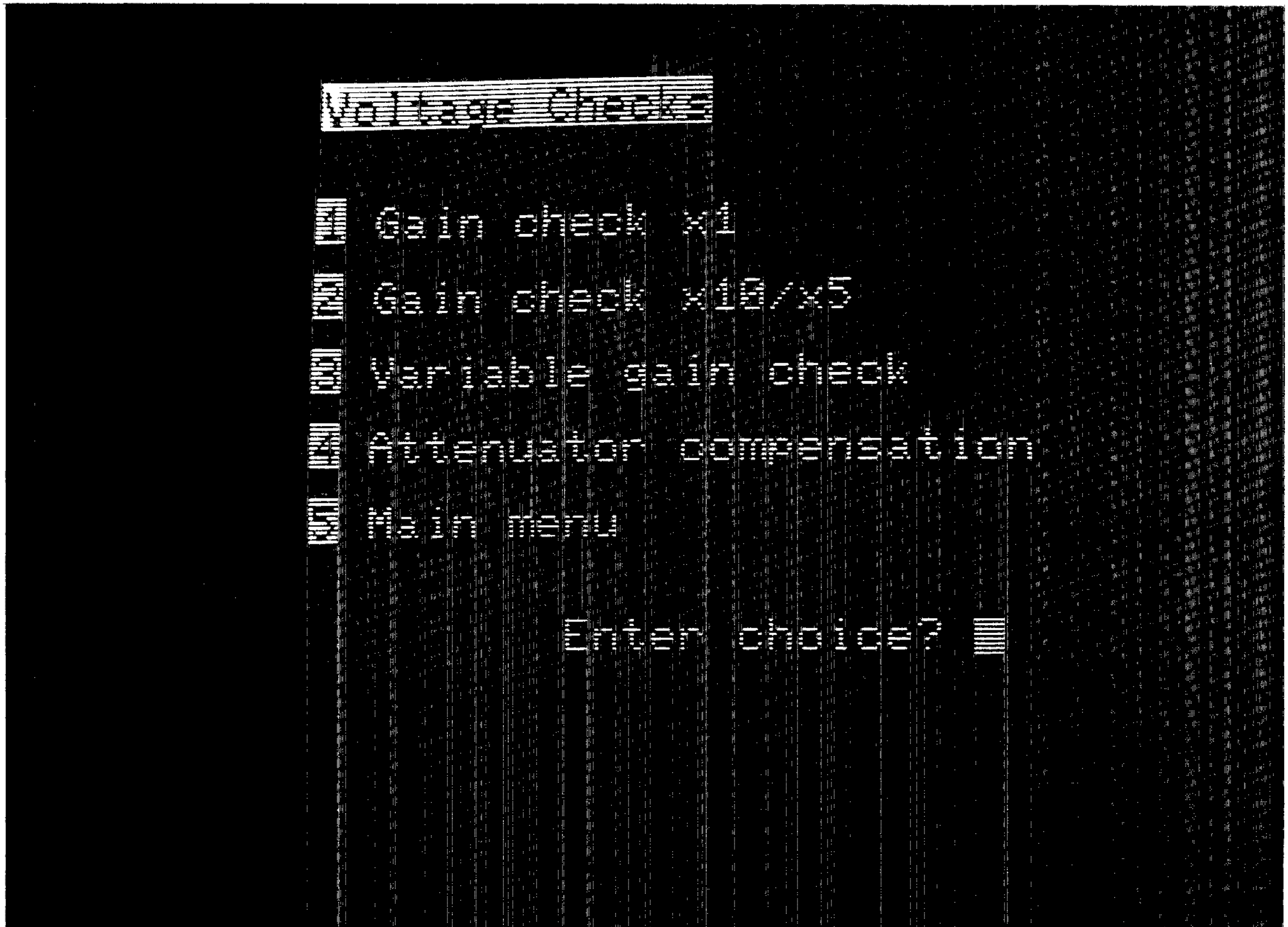

FIGURE 6. TYPICAL SUB MENU FOR VOLTAGE CHECKS.

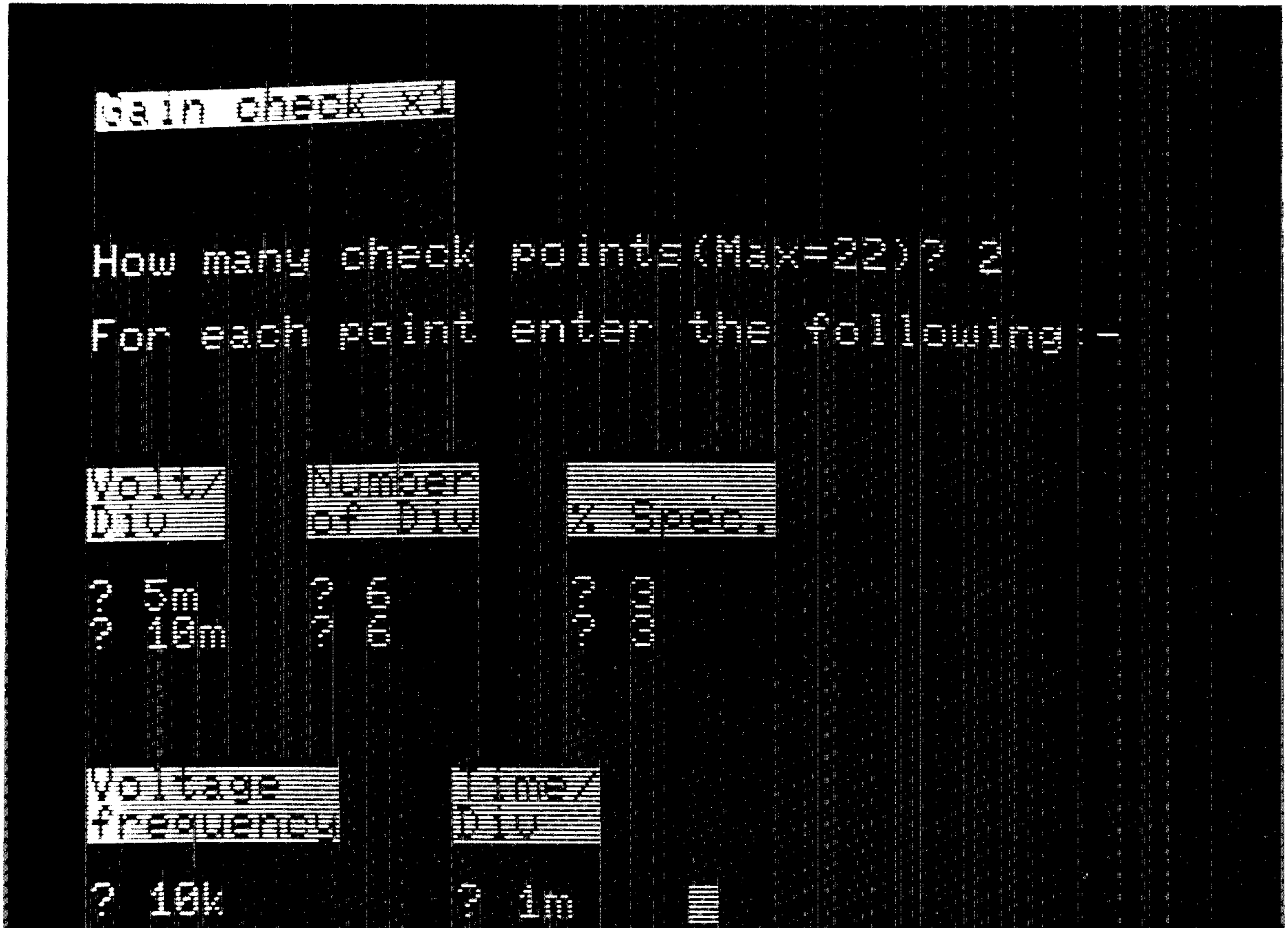

FIGURE 7. FILL—IN TABLE AFTER SELECTING OPTION 1 FROM VOLTAGE CHECK SUB MENU (FIGURE 6)

CERTIFICATE OF CALIBRATION

Manufacturer.....Ballantine
Model no.........1022A
Serial no........021-553

Procedure No....QA-III(final)
Operator........Roger A. Stagnol
Date............12/15/82

TEST TITLE	CHANNEL/ TIME BASE	TEST VALUE	GIVEN TOLERANCE	MEASURED ERROR	PASS/ FAIL
DC-GND-AC	CH 1	DC-GND	.1 D	0 D	Pass
	CH 1	GND-AC	.1 D	.01 D	Pass
ATTEN. BAL.	CH 1	2v-5mv	.1 D	.01 D	Pass
VAR ATTEN. DC BAL.	CH 1	5mv	.1 D	0 D	Pass
DC-GND-AC	CH 2	DC-GND	.1 D	.01 D	Pass
	CH 2	GND-AC	.1 D	0 D	Pass
ATTEN. BAL.	CH 2	2v-5mv	.1 D	0 D	Pass
VAR ATTEN. DC BAL.	CH 2	5mv	.1 D	.02 D	Pass
VOLTS GAIN (x1)	CH 1	5mv	+/- 3%	-00.0%	Pass
	CH 1	10mv	+/- 3%	-00.1%	Pass
	CH 1	20mv	+/- 3%	-00.1%	Pass
	CH 1	50mv	+/- 3%	-00.1%	Pass
	CH 1	.5v	+/- 3%	-00.2%	Pass
VAR VOLTS GAIN (x1)	CH 1	5mv	2.4 D	2 D	Pass
VOLTS GAIN (x1)	CH 2	5mv	+/- 3%	-00.2%	Pass
	CH 2	10mv	+/- 3%	-00.0%	Pass
	CH 2	20mv	+/- 3%	+00.0%	Pass
	CH 2	50mv	+/- 3%	+00.0%	Pass
	CH 2	.5v	+/- 3%	+00.1%	Pass
VAR VOLTS GAIN (x1)	CH 2	5mv	2.4 D	1.8 D	Pass
DC TRIG. MODE	TB A	.1mS	n/a	n/a	Pass
TRIG SENSITIVITY	TB A(+)	.1mS	.2 D	.3 D	Fail
	TB A(+)	.1mS	.2 D	.2 D	Pass*
	TB A(-)	.1mS	.2 D	.2 D	Pass
TIMING ACCURACY	TB A	1uS	+/- 3%	+00.1%	Pass
	TB A	10uS	+/- 3%	+00.4%	Pass
	TB A	50uS	+/- 3%	+00.5%	Pass
	TB A	.1mS	+/- 3%	+00.7%	Pass
	TB A	.1S	+/- 3%	+00.4%	Pass
TIMING ACCURACY(x 10)	TB A	1uS	+/- 5%	+02.1%	Pass
RISE TIME CHECKS	CH 1/TB A	1uS(x 10)	5%	3.3%	Pass
	CH 1/TB A	1uS(x 10)	24nS	16.5nS(21.2MHz)	Pass
RISE TIME CHECKS	CH 2/TB A	1uS(x 10)	5%	3.5%	Pass
	CH 2/TB A	1uS(x 10)	24nS	16.8nS(20.8MHz)	Pass
X-Y(phase shift)	5mV/CH.1 & DC to 10kHz		3 Degrees	2 Degrees	Pass

* Indicates results after adjustments.

Calibration time...00H. 06M. Passed on all tests.
Produced on a Ballantine 4000A COMPUTEST Automated Calibration System.

....

FIGURE 8. TYPICAL BALLANTINE COMPUTEST SYSTEM CALIBRATION CERTIFICATE.

FIGURE 9. BALLANTINE 6127A – "MECCA"
PROGRAMMABLE OSCILLOSCOPE CALIBRATOR

AUTOMATED CALIBRATION SYSTEMS AT NBS

AN OVERVIEW

Arthur O. McCoubrey
National Bureau of Standards
Washington, D.C. 20234

INTRODUCTION

Automation of calibration systems at the National Bureau of Standards began when minicomputers suitable for dedicated applications became available more than fifteen years ago. Progress was substantially accelerated, about ten years ago, when a special NBS program was initiated to make minicomputers available and encourage their use for laboratory automation. This program involved the establishment of a technically competent support group to provide consulting help and the purchase of standardized hardware in quantity lots. A significant part of the computer technology now incorporated in automated calibration systems resulted directly from this program. Progress was further accelerated by the advent of microcomputers and particularly, during the past six or seven years, the availability of increasingly large random access memories and low cost mass storage media.

The policy of making computer technology readily available to NBS engineers and scientists has continued and a coordinated selection of board level microcomputer components, peripheral devices and commercial software, has been available from storeroom supplies for the past three or four years.

The storeroom components, originally selected for eight bit microprocessor compatibility, are gradually being extended to include the sixteen bit microprocessors. It is possible to assemble a wide range of

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Note: Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

special purpose computer configurations using storeroom components, and their availability tends to promote a higher level of hardware and software coordination among different users.

General Considerations

Calibration automation at NBS involves a number of unique considerations; for example:

- o the automated systems must function at, or very close to, the state-of-the-art for realizable accuracy within each specific measurement technology;
- o calibration results of each automated system must support acceptable methods for the dissemination of units of measurement at the highest levels of accuracy; (uncertainty statements, etc.)
- o in contrast to the dominant requirements for industry and for military system support facilities, automated calibration systems at NBS are usually not required to process large numbers of devices submitted for test. However, they are generally required to acquire large volumes of data for each unit tested and data processing operations are usually more extensive.
- o a significant number of automated calibration systems at NBS have been developed for calibration operations that otherwise would not be possible or practical because of the cost and time involved or because there is no alternate way to acquire the measurement data in the time available.

These considerations not only tend to distinguish the automated calibration systems at NBS from those developed elsewhere, they also lead to very different approaches to automation in the different NBS calibration laboratories.

AUTOMATED CALIBRATION SYSTEMS AT NBS

The calibration systems that have been automated at NBS are listed in Table I within groups for the different measurement quantities involved. With only the few exceptions indicated, all of these systems are utilized for routine NBS services described in NBS' catalog of calibration services, Special Publication 250. Two of the systems, marked by asterisks, are usea only for internal NBS calibration requirements. Four of the systems listed in Table I are in advanced stages of construction; they will be used for routine services when they are complete.

Automated Functions

Functions that are automated in the various calibration systems are summarized in Table II. Not all of these functions are automated in every system and some functions, particularly in some areas of information storage and retrieval, are automated in only a few systems to a very limited extent. In fact, there has been almost no effort, up to the present time, to create or utilize files for administrative purposes. In many cases the cost to do this would be relatively low.

It is interesting to consider the dominating driving forces that have motivated calibration automation at NBS; they have not been the same, of course, for every case. In the earliest days, data acquisition appears to have been the motivating objective in most cases. Most of the data processing was probably done by a computer at that time, but an off-line data transfer to an independent machine was often involved. As the cost of computer capacity decreased, the data acquisition and data processing functions were more often integrated within a single automated system. however, in some cases two dedicated central processing units have been used.

There are several calibration systems at NBS for which data processing provides the motivating objective for the use of a computer. In some of these cases measured data are still entered manually. Such systems have not been included here.

There is at least one case for which the automation of apparatus control constituted the dominant motivating objective. In this case, involving pressure calibrations, the test cycle requires 336 observations in less than 3 seconds. The procedure would not be possible without automation of the apparatus.

The several specific functions listed under the general function headings in Table II are self-explanatory in most cases. Systematic error sources are intended to include departures of calibration apparatus from ideal performance. For example, in some cases the apparatus may include a lead screw to implement a necessary motion. Departures from linearity of the lead screw cause errors in the knowledge of position. Such departures may be carefully measured and stored in a file as part of the characterization of the apparatus. Thls file may then be called to adjust position values in measured data in order to increase the accuracy of results.

Most of the automated calibration systems at NBS include the use of relatively complex statistical routines including such operations as convolution and deconvolution. The Fast Fourier Transform is used in two systems and curve fitting routines are used in several cases. In general, the specialized programs for the mathematical routines are resident in accessible files and called by the data processing program.

The data processing functions listed in Table II include Go-No-Go decisions. Such decisions are based on the comparison of measured quantities, or quantities derived from measurements with predetermined criteria and, depending upon the result, causing some action to take place under the control of the computer. Such actions include special signals to the system, printing appropriate text in reports, stopping the calibration procedure or changing the calibration protocol to a more appropriate option.

The apparatus control function generally involves the control of the adjustable parameters of the apparatus in accordance with a calibration protocol that has been incorporated in a stored program. In principle, environmental conditions prevailing during test, as well as other factors, may also be controlled by the automated calibration system facilities. However, at the present time such factors are controlled independently in the systems at NBS with the possibility of limited exceptions in a few cases.

Table III suggests the extent to which the functions listed in Table II are automated in the calibration systems listed in Table I. There *is* far too much information to discuss in any detail, however, the trends are of interest. In particular, this chart indicates that all of the automated calibration systems at NBS include extensive control of data acquisition functions and data processing functions. While the automation of apparatus control is not broken down into much detail, there is also a substantial amount of automation in this area. In the case of functions related to report generation, the automation is more limited. While all systems store system related information to some extent, the automation of storage and retrieval functions is still very limited in other functional areas. The expansion and manipuletion of data bases for administrative purposes has not been included to any significant extent, if at all.

Computer Technology Utilized

Table IV lists the elements of computer technology that have been incorporated into NBS automated calibration systems up to the present time. The most recent generation of microcomputers, based upon the sixteen bit microprocessors, are not yet represented among the systems in routine use; otherwise, the scope of the technology used reflects the state of the art. In the software area, most of the applications programs have been written in the high level languages, particularly BASIC. Only a limited amount of software for calibration purposes has been written in the assembly language for the machine involved. In the recent development of the automatic calibration system for water flow measuring devices a commercial data base management program package has been incorporated as an element of the software. This approach adds very powerful capabilities to the system. Such capabilities would not be practical to achieve through the use of internal programming resources. It is reasonable to anticipate that the use of specialized commercial software packages will become more frequent in future automated calibration systems.

Table V indicates the application of the elements of computer technology listed in Table IV to the different automated calibration systems listed in Table I. Again, there is too much information to discuss in detail; however, this chart will be made available to anyone who is interested. More extensive technical information may be obtained by contacting the persons listed in this chart.

Impact of Calibration Automation at NBS

While the benefits of automated calibration systems at NBS are very significant, it is important to recognize that they differ substantially among the several systems. Therefore, it is not possible to define benefits of an entirely general nature. However, it is useful to identify the areas in which the benefits of automation are most often realized.

- Increased accuracy and/or precision

A significant number of calibration systems at NBS perform at accuracy levels and/or precision levels that are increased by automation. These benefits usually result from the use of more extensive statistical routines to process larger quantities of measured data than otherwise practical. Accuracy and precision are also improved by more extensive treatment of systematic errors using complex mathematical models for the apparatus and larger quantities of measured data that characterize the systematic error sources.

- Control of calibration quality

Whether or not the automation of calibration systems results in increased accuracy and precision, there is a very substantial enhancement of calibration uniformity and control of factors that cause unexpected and degrading results. To a large extent this benefit results from the elimination of human errors caused by fatigue and related factors. However, there are additional contributions from the capacity to process redundant measurements, detect anomalies in reference standards and measuring apparatus and to sense unexpected variations in test conditions.

- Reduction of labor intensive procedures

There is a clear benefit from the automation of calibration systems in terms of increased work volume based upon a smaller amount of human labor. Two factors are involved in increased productivity. In the first place it is not necessary to employ technicians for the routine task of changing test parameters and recording data; in the second place the skilled people that must be available generally need not devote continuous attention to the calibration system operation. They become free, in many cases, to use a substantial amount of their time engaged in other activities.

While the labor productivity benefits of calibration automation are very positive, it is important to recognize that the technical demands upon the metrologist and the metrology technician are increased. It is necessary for these people to understand, in depth, the computer technology they utilize and play a major role in the implementation and support of it. Computer experts may make important contributions to system design and construction but their lack of detailed knowledge of the metrology involved makes it necessary for the calibration system experts to play an important and continuing role related to the use of computer technology. This applies to software as well as hardware.

- Implementation of otherwise impossible procedures

A significant number of the calibration procedures now used at NBS would not be practical in the absence of automation; in some cases they would not be possible, since the required quantities of measured data are beyond reasonable capabilities for manual systems. In other cases the complexity of the data processing is the controlling factor. In still other cases the measured data must be acquired in such a short time interval that non-automated procedures are not possible.

An example of the first case is found in the calibration of surveyor's leveling rods that now must be calibrated at each of 600 intervals. At each interval a statistically significant sample of data must be acquired. The volume of data, as well as the related processing, is the dominating factor in the requirement for automation.

Examples of the second case are found in the calibration of acoustic transducers and in time domain metrology. In both of these cases the data processing requires the use of the fast Fourier transform to obtain the parameters of power spectra and pulse shapes. In the case of time domain metrology deconvolution routines are also used to obtain pulse shape parameters from measurements overlaid by noise.

An example of the third case is found in the pressure calibration system based upon the acoustic manometer. In this case the procedure involves the measurement of manometer column lengths using an acoustic interferometer. Statistically significant samples of data must be obtained at each pressure setting. Very small pressure drifts occur as a result of temperature fluctuations in the millikelvin range, and it is necessary to obtain more than 300 individual measurements within a two or three second interval for which the pressure drift is not a limiting factor.

The Future

The automation of calibrations at NBS will certainly continue with emphasis on data acquisition, data processing and apparatus control. It may be expected, however, that there will be an increasing emphasis on the manipulation of larger data bases, including the storage and retrieval of long term records on standards submitted for calibration. Such records now exist in many cases in traditional files. More extended use of powerful commercial software packages should prove to be very helpful in this connection.

It may also be expected that advancing microprocessor technology will be rapidly utilized in NBS automated calibration systems, particularly in view of the larger random access memories that are available for use with it. Finally, it is recognized that improved techniques, including array processors, for increasing the speed of processing large quantities of data will become important in future generations of automated calibration systems.

Table I

Automated Calibration Systems at NBS

Electrical Quantities (d.c. and low frequency)

Standard Cell Comparator
Resistance Calibrator (l-ohm)
A.C./D.C. Voltage Difference
A/D and D/A Converters

Electromagnetic Quantities (involving coaxial lines, wave guides and optical fibers)

Automatic Network Analyzer I (first generation)
Automatic Network Analyzer II (six-port)
Near Field Antenna Systems
Time Domain Waveform Metrology

Dimensional Quantities

Line Scale Interferometer
Surveyor's Leveling Rods
Three Dimensional Measurement Facility
Gage Blocks
Angle Gage Blocks
Measuring Wires for Threads
Optical Flats
Surface Finish

Time and Frequency

Temperature

Thermocouples
Cryogenic Thermometers
Temperature Fixed Points
Gas Thermometry'
Platinum Resistance Thermometers
High Sensitivity Temperature Transducers'

Volume and Flow

Water Flow Rate+
Gas Flow Rate+

Force and Acceleration

Accelerometers System I (vibration transducers)
Accelerometers System II (extended high frequency testing)+

Optical Radiation Quantities

Spectroradiometer (FASCAL)
High Accuracy Spectrophotometer

Ionizing Radiation Quantities

X-ray and Gamma ray Dosimeters
Dosimetry for High-Dose Applications

'Routine calibration service (SP-250) not available
+Automation in progress.

Table II

Automated Calibration Systems at NBS
Automated Functions

1.0 Data Acquisition

- 1.1 Primary data
- 1.2 Influence factors (temperature, pressure, humidity, etc.)
- 1.3 Systematic error sources (apparatus anomalies, etc.)
- 1.4 Characteristics of local reference standards

2.0 Data Processing

- 2.1 Raw data reduction
- 2.2 Adjustments for systematic errors
- 2.3 Adjustments for influence factors
- 2.4 Mathematical routines (statistics, convolution, deconvolution, F.F.T., curve fitting, etc.)
- 2.5 Go/No-go decisions
- 2.6 Trend analysis

3.0 Apparatus Control

- 3.1 Test parameters
- 3.2 Test conditions

4.0 Report Generation

- 4.1 Graphics
- 4.2 Charts and Tables
- 4.3 Test reports
- 4.4 Local reference standard status reports

5.0 Information Storage and Retrieval

- 5.1 System information
- 5.2 Local reference standards history
- 5.3 Customer standards history
- 5.4 Calibration activity levels
- 5.5 Administrative information

Table III

NBS Calibration Automation
Automated Functions

General Functions	1. Data Acquisition				2. Data Processing						3. Apparatus Control		4. Report Generation				5. Information Storage & Retrival				
Specific Functions (See Table II)	1	2	3	4	1	2	3	4	5	6	1	2	1	2	3	4	1	2	3	4	5
Standard Cell Comparator	X		X	X	X	X	X	X		X	X		X	X	X	X	X	X			
Resistance Calibrator (1-ohm)	X		X	R	X	R	R	R		R	X	X	R	R	R	R	X	R			
A.C./D.C. Voltage Difference	X		X	X	X	X		X	X		X	X	X	X			X				
A/D and D/A Converters	X			X	X			X			X	X	X	X	*		X				
Automatic Network Analyzer I	X		X	X	X			X	X		X	X	X	X	X		X				
Automatic Network Analyzer II	X	X	X	X	X	X	*		X	X	X	X					X				
Near Field Antenna System	X		X	X	X	X		X			X		X	X			X				
Time Domain Waveform Metrology	X		X	X	X	X		X	X	X		X	X	X			X				
Line Scale Interferometer	X	*		X	X	X	X	X			X	X	X	X	*		X				
Surveyor's Leveling Rods	X				X	X	X	X			X		X	X	X		X				
Three Dimensional Measuring Facility	X	X	X		X	X	X	X		X	X		X	X	X		X				
Gage Blocks	X		X	X	X	X	X	X	X	X				X	X	X	X	X			
Angle Gage Blocks					X	X		X	X					X	X	X	X				
Measuring Wires for Threads					X	X		X	X						X		X	X			
Optical Flats					X			X							X	X	X				
Surface Finish	X		X	X	X	X		X	*		0		X	X		X	X	X			

R - Implemented on a remote system using a

* - Planned

O - Partially automated

Note: Column numbers correspond to subheadings in Table II. For example, column 1 under Data Acquisition in Table III refers to 1.1 under Table II, column 2 refers to 1.2 in Table II, etc.

Table III continued

General Functions	1. Data Acquisition				2. Data Processing						3. Apparatus Control		4. Report Generation				5. Information Storage & Retrival				
Specific Functions	1	2	3	4	1	2	3	4	5	6	1	2	1	2	3	4	1	2	3	4	5
Thermocouples	X		x	x	x	x		X			X			X			X				
Cryogenic Thermometers	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X				
Temperature Fixed Points	X	X	X	X	X	X	X	X			X	X		X			X				
Gas Thermometry†	X	X	X	X	X		X	X						X		X	X	X			
High Sensitivity Transducers †	X	X	X	X	X	X	X	X			X	X	X	X			X				
Ultrasonic Manometer	X	X	X	*	X	X	X	*	X		O						X				
Water Flow Rate	X	X	X	X	X	X	X	X		*	O	*	X	X	O	X	X	X	X	O	
Gas Flow Rate	*	*		*	*	*	*	*		*			*	*	*	*	*	*	*		
Accelerometer System I	X		X	X	X	X		X	X		X		X	X	X		X				
Accelerometer System II	X				X			X			X	X	X	X	X		X				
Acoustic Emission Transducers	X				X			X					X		X		X				
Spectroradiometer (FASCAL)	X		X	X	X	X	X	X		X	X	X	X	X			X				
High Accuracy Spectrophotometer	X		X	X	X	X		R		X	X	X	R	R			X				
X-ray and Gamma ray Dosimeters	X	X		X	X		X	X	*	X	X	X	R	)X	R		X				
Dosimetry for High-Dose Applications	*	X	X	X	*	X	X	X	X	X	X	X	X	X	X	X	X				
Time and Frequency	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X		

R - Implemented on a remote system using a communications link

† - Internal NBS services

* - Planned

0 - Partially automated

Table IV

NBS Calibration Automation Computer Technology Used

1.0 CPU

- 1.1 Microcomputers
  - 1.1.1 Custom Z-80/S-100 (NBS Storeroom Components)
  - 1.1.2 Commercial Z-80/S-100 (Cromemco or Industrial Micro Systems)
  - 1.1.3 Desk Top Computers (H-P 85 or H-P 9800 Series)
  - 1.1.4 Apple II
  - 1.1.5 Tektronix 4054
- 1.2 Minicomputers
  - 1.2.1 Perkin-Elmer 7/16
  - 1.2.2 Perkin-Elmer 7/32
  - 1.2.3 H-P 2116-C
  - 1.2.4 NOVA 1200
  - 1.2.5 PDP 11 Series
- 1.3 Central Mainframe
  - 1.3.1 Univac 1182

2.0 RAM

- 2.1 Semiconductor
- 2.2 Magnetic core

3.0 Mass Memory

- 3.1 Floppy Disks
- 3.2 Hard Disks
- 3.3 Tape (cassette)
- 3.4 Tape (9 track)

4.0 Input/Output

- 4.1 Console
  - 4.1.1 CRT
- 4.2 Hard Copy
  - 4.2.1 Printer
  - 4.2.2 Plotter
- 4.3 Instrument Interface
  - 4.3.1 IEEE/488 and HPIB
  - 4.3.2 MIDAS
  - 4.3.3 Custom
  - 4.3.4 RS 232

5.0 Programming Language(s)

- 5.1 Assembly
- 5.2 Fortran
- 5.3 Basic
- 5.4 Pascal
- 5.5 HPL

Table V

NBS Automated Calibrations Computer Facilities Utilized

	CPU: Micro: Custom Z-80/S-100	CPU: Micro: Commercial Z-80/S-100	CPU: Micro: Desk Top	CPU: Micro: Apple II	CPU: Micro: Tektronix 4054	CPU: Mini: Interdata 7/16	CPU: Mini: Interdata 7/32	CPU: Mini: H-P 2116-C	CPU: Mini: NOVA 1200	CPU: Mini: PDP 11 Series	RAM: Semiconductor and/or Magnetic Core	Mass Memory: Floppy Disk	Mass Memory: Hard Disk	Mass Memory: Tape (cassette)	Mass Memory: Tape (9 track)	Input/Output: CRT Consol	Input/Output: Printer	Input/Output: Plotter	Input/Output: Instrument Interface: IEEE-488 & HPIB	Input/Output: Instrument Interface: MIDAS	Input/Output: Instrument Interface: Custom	Input/Output: Instrument Interface: RS-232	Programming Languages: Assembly	Programming Languages: Fortran	Programming Languages: Basic	Programming Languages: Pascal	Programming Languages: HPL	In a network	Dedicated	Technical In[illegible]on
Standard Cell Comparator						X	X					X	X			X	X	X		X				X	X			X		J. Sims 301-921-3606
Resistance Calibrator (1-ohm)	X										64K	X				X	X		X	X			X		X			X		R. Dziuba 301-921-2715
A.C./D.C. Voltage Difference			X								64K			X		X	X	X	X								X	X		K. Lentner 301-921-2727
A/D D/A converters					X						64K			X		X	X	X	X		X			X	X			X		M. Souders 301-921-2727
Automatic Network Analyzer (I)								X			32K	X				X	X	X	X						X			X		C. Hoer 303-497-3705
Automatic Network Analyzer (II)			X								256K	X				X	X		X		X				X			X		C. Hoer 303-497-3705
Near Field Antenna System						X					64K	X				X	X	X			X			X	X			X		A. Newell 303-497-3743
Time Domain Waveform Metrology									X		64K	X	X	X		X	X	X	X		X		X	X					X	W. Gans 303-497-3538
Time and Frequency							X(2)				256K,375K	X	X		X	X	X	X			X	X	X					X	X	S. Stein 303-497-3335
Line Scale Interferometer			X								198K			X		X	X	X	X						X				X	J. Beers 301-921-2216
Surveryor's Level Rods							X				768K		X			X	X	X				X		X	X			X		L. Caroll 301-921-2216
Three Dimensional Measuring Facility							X				768K	X	X			X	X		X		X	X	X	X	X			X		T. Charlton 301-921-2216
Gage Blocks							X				768K		X			X	X		X			X			X			X		L. Caroll 301-921-2216
Angle Gage Blocks							X				768K		X			X	X					X			X			X		L. Caroll 301-921-2216
Measuring Wires for Threads							X				768K		X			X	X					X		X	X			X		L. Caroll 301-921-2216
Optical Flats							X				768K		X			X	X					X		X				X		L. Caroll 301-921-2216
Surface Finish							X				256K		X		X	X	X	X			X				X				X	T. Vorburger 301-921-3838
Thermocouples		X									64K	X				X	X		X										X	M. Scroger 301-921-2069
Cryogenic Thermometers						X					64K	X	X			X	X		X					X					X	E. Pfeiffer 301-921-2741
Temperature Fixed Points	*										64K	*				X	X		X						X			*		J. Schooley 301-921-3315
Gas Thermometry		X									64K	X				X	X		X						X				X	R. Edsinger 301-921-2076
High Sensitivity Transducers (3)						X					64K	X				X	X	X	X					X				X	X	C. Van Degrift 301-921-2753
Ultrasonic Manometer		X									64K	X				X	X		X						X			X		C. Tilford 301-921-2121
Water Flow Rate		X									64K	X	X			X	X	X	X						X[1]			X		J. Whetstone 301-921-3681
Gas Flow Rate		*									64K	*	*			*	*	*	*						*			*		J. Whetstone 301-921-3681
Accelerometer System I			X								187K	X				X	X	X	X			X			X			X		M. Serbyn 301-921-3607
Accelerometer System II			X								128K					X	X	X	X			X			X			X		M. Serbyn 301-921-3607
Acoustic Emission Transducers							X				500K(2)	X	X			X	X	X			X			X	X					F. Breckrenridge 301-921-3646
Spectroradiometer (FASCAL)		X									64K	X				X	X	X	X	X			X		X			X		J. Walker 301-921-3613
High Accuracy Spectrophotometer (3)		X									64K	X				X	X	X			X				X			X	X	K. Eckerle 301-921-2791
X-ray and Gamma ray Dosimeters (3)			*				X				64K	X	X			X	X	R	*		X		X		*			X	X	T. Loftus 301-921-2361
Dosimetry for High-Dose Applications				X							48K	X				X	X	X			X					X			X	J. Humphreys 301-921-2201

(1) - This system also uses a commercial data base management software package.

(2) - Shared system; 40K used for this service.

(3) - This system also uses Central Mainframe (1182).

*Planned

CALIBRATION SYSTEM AUTOMATION AT GRUMMAN AEROSPACE CORPORATION

Charles E. Weber
Engineering Supervisor
Measurement Standards Section
Quality and Safety Operations
Grumman Aerospace Corporation
Bethpage, New York

CALIBRATION SYSTEM AUTOMATION AT GRUMMAN AEROSPACE CORPORATION

Calibration automation at Grumman Aerospace Corporation had its beginnings in the late 1960s. At that time, the company's calibration facilities were under great stress dealing with a peak workload which exceeded 80,000 calibration and repair operations per year. Active aerospace programs supported by the calibration laboratories covered an extremely wide application range resulting in a very diverse calibration and repair workload.. The major programs included:

- Lunar Module (LM) - Moon lander, Project Apollo
- F-14 (Tomcat) - Fleet defense aircraft
- A-6 (Intruder) - All weather fighter/bomber
- EA-6 (Prowler) - Electronic warfare system
- E-Z (Hawkeye) - Fleet surveillance and control system
- C-Z (Greyhound) - Fleet cargo aircraft
- OV-1 (Mohawk) - Army surveillance system
- Gulfstream II - Corporate jet

Approximately 250 personnel were directly involved in the calibration effort at the Long Island laboratories in 1969, the peak workload year. Fourteen years later, the Measurement Standards section of Grumman Aerospace Corporations' Quality and Safety Operations Department is utilizing 98 personnel to process 56,000 calibration and repair operations per year. The number of personnel involved has decreased at a rate two times faster than the decrease in workload. While some of the productivity increase is due to organizational and procedural changes, a substantial portion is attributable to the successful application of automation to the calibration process. The balance of this presentation will describe the automated calibration systems that have been utilized by Grumman Measurement Standards and the next generation of automated calibration systems which will be in operation at Grumman during 1983.

It is interesting to note that the major aerospace programs supported by the Measurement Standards calibration laboratories today are to a very large extent the same ones that existed in the late 1960s. Today's major programs include the previously mentioned F-14, A-6, EA-6, E-Z, C-Z and and OV-1 aircraft with the following additional programs:

- EF-111 - Air Force electronic warfare system
- Space Shuttle Wing
- Aerostructures
  - subassemblies for Boeing 757 and 767,
  - subassemblies for Cammacorp re-engining of McDonnell-Douglas DC-8

While the supported programs appear to be very similar to those existing previously, their impact on Measurement Standards' workload has changed considerably. The later model aircraft, along with the new programs, have greatly increased the complexity of the workload. Requirements for tighter tolerances and broader ranges have impacted every measurement parameter.

AUTOMATED PRESSURE CALIBRATION SYSTEM

The first automated calibration system at Grumman became operational in 1968 (Figure 1). It was specifically designed to calibrate the large quantities of pressure transducers used on the LM program and the flight test programs for the various aircraft. The system is composed of a control and data acquisition section provided along with proprietary software by Hewlett Packard. The computer used is a Hewlett Packard 2114A. Measurement Standards interfaced this with a set of Gilmore, Model 289, programmable pneumatic dead weight pressure calibrators. Programs were originally on punched tape with operator data input and data output made through a Teletype. However, this system was shortly thereafter upgraded to use a Texas Instruments 700 dual tape cassette terminal for program input and data input and output

The automated pressure calibration system covers the range of 1 to 6,000 psi at an accuracy of 0.05% of reading.

The calibration program for transducers includes absolute accuracy, linearity, hysteresis, and repeatability. Up to 10 transducers of similar range can be run simultaneously. Automatic data acquisition and analysis provides a complete data package including necessary correction factors required by the end user of the transducers. On average, calibration and data reduction times have been reduced by approximately 75% as compared to manual methods.

Unfortunately, a combination of old age and new requirements has caught up with this system. It is now in the process of being phased out. During the past few months, control and data processing has been shifted to a new Fluke 1720A computer. New software, developed by Measurement Standards, is stored and used in disk form. Replacement of the programmable pressure calibrators and the data acquisition system will occur in the near future.

AUTOMATED AIR DATA TEST SET CALIBRATION SYSTEM

A new, smaller scale, automated pressure calibration system (Figure 2) has been developed specifically for calibration of air data test sets. These test sets are widely used for flight line checking of aircraft air data computers. The calibration system consists of a Ruska 6000 Automatic Air Data Test Set controlled via a Fluke 1720A Computer. This system covers the range of 32 in. of mercury absolute and up to 200 in. of mercury differential pressure. Calibration data for the unit under test is produced automatically (Figure 3).

AUTOMATED THERMOCOUPLE CALIBRATION SYSTEM

The original pressure calibration system proved to be so effective in reducing calibration time that it was soon obvious that there was sufficient availability of the data acquisition and control system to allow its use for other tasks. The data acquisition system was designed for high accuracy at millivolt input levels making it ideal for thermocouple calibration. An existing thermocouple calibration furnace was made oroorammable and interfaced with the comouter control svstem.

Software was developed by Grumman. The thermocouple calibration system had a capability of calibrating up to 18 thermocouples over a temperature range of 200" to 1800°F. Accuracy levels were ±3°F. In operation, the system compared thermocouples under test against a reference thermocouple. Thermocouple outputs were linearized by the computer, compared against allowable tolerances and presented on an automatically produced data sheet.

On average this system reduced calibration labor by approximately 95% per unit compared to manual calibration methods. In addition, the queue for thermocouple calibration was greatly reduced since the operation could run untended at night and over weekends and holidays.

Higher accuracy requirements and increased workload have necessitated the development of a completely separate thermocouple calibration system. The new calibration system was put on Tine in 1982 (Figure 4). This system utilizes the same thermocouple furnace with a Grumman designed control end data acquisition system. A Hewlett Packard 98458 computer is used for control and data processing functions. Software was developed by Grumman. The system again develops a complete data sheet (Figure 5) during the course of a calibration. Calibration accuracy has been improved to ±1°F. using the new system over the same 200" to 1800°F. temperature range. This was made possible by tighter control of the furnace and improved data acquisition.

AUTOMATED METER CALIBRATOR

Grumman's first venture into automating the calibration of electrical measuring equipment focused on the lowly multimeter which existed and still exists in large quantities in the Grumman inventory. An ESI System 70 Meter Calibrator was placed in service in 1970. This system, designed specifically for multimeters and other analog meters, was controlled by pre-programned punch-cards and proved to be quite effective. As a proof of Murphy's Law however, shortly after this system was operational it was determined that most multimeters were not being used for qualitative measurements. As a result, they were placed on a "No Calibration Required" status, thus eliminating the major portion of the ESI-70s workload. Accuracy constraints prevented this system's use for calibrating the oncoming wave of digital multimeters.

AUTOMATED DC-LOW FREQUENCY CALIBRATION SYSTEM

Although Measurement Standards continued investigating many proposed automated calibration systems for electrical and microwave instruments, it was not until 1974 that systems having adequate performance and broad application began to appear on the market. An evaluation and competitive bid procedure led to the purchase of a Julie Research Locost 106 System (Figure 6). The system was delivered and placed in service in May Of 1976. The Julie System as originally configured consisted of Julie AC and DC voltage and current sources, a resistance source, a voltage divider, a digital multimeter and necessary interface and control hardware. The controller was a Hewlett Packard 9830A computer. Proprietary software was supplied by Julie Research on tape cassettes. Nominal specifications for the system as it is configured today are shown below although many can be upgraded by simple self calibration, transfer, or laddering techniques in order to meet the need for higher accuracy:

Parameter	Mode	Ranges	Accuracy (% Rdg)
DC Volts	Generate	0-1200V	Ø.ØØ1 - Ø.ØØ5%
	Measure	1.2uV to 12oov	Ø.ØØ1 - Ø.ØØ3%
AC Volts	Generate	100uV to 12Øv	Ø.Ø25% 20Hz - 2ØkHz Ø.Ø5% 2ØkHz - 100kHz Ø.2% 100kHz - 1MHz
		100V to 12ØØV	Ø.Ø35% 50Hz - 10kHz Ø.Ø5% 20Hz - 50Hz Ø.1% 10kHz - 100kHz
	Measure	0-1000V	Ø.Ø1% DC - 50kHz
DC Current	Generate	Ø to 12A	Ø.ØØ3 - 0.005%
	Measure	Ø. to 12A	Ø.Ø1%
Resistance	Generate	Ø to 10 Megohms	Ø.ØØ5 - Ø.Ø1%
	Measure	Ø to 1Ø Megohms	Ø.ØØ2 - Ø.ØØ5%
Ratio	Measure	Ø to 1.2	Ø.ØØØ25%
AC Current	Generate	Ø to 2A	Ø.Ø5%
Frequency Response	Generate	10Hz to 12MHz	Ø.5% to 2% of level

Units to be calibrated having parallel BCD data output can be interfaced to the system via simple signature cards which are used to match the unit to the universal data input. System availability has been better than 95% for the almost seven years that it has been in service. The JRL-1Ø6 handles the calibration of a wide variety of instruments including:

- Digital and analog meters
- Voltage calibrators
- Current calibrators
- Resistance decades
- Resistance bridges
- Potentiometers
- Temperature indicators
- Current shunts
- Voltage dividers
- Amplifiers

A full calibration data sheet is prepared automatically for each instrument (Figure 7). Calibration times for the instruments listed have been reduced by as much as 9Ø%.

The successful utilization of this system was a key factor in Grumman's decision to enter the commercial calibration and repair services field. The services provided to our commercial customers now approximate 2Ø% of Measurement Standards' workload.

AUTOMATED DC- LOW FREQUENCY CALIBRATION SYSTEM UPDATE

It might be reasonably thought that a seven year old system couldn't be "state of the art" as this years' Measurement Science Conference theme stresses. However, a combination of the initial high performance level of the system, judicious hardware upgrades made possible by modular design, and adaptable software has kept this system at state of the art levels.

System capabilities have been significantly upgraded in the following areas (Figure 8):

- DC voltage measuring capability was extended to 1 millivolt full scale by adding a Julie Research BA-1Ø8 amplifier
- AC voltage measuring capability was added through use of a Ballantine 1600A Automatic Thermal Transfer Standard
- Extended frequency response capability was added through a Fluke 6011A Synthesizer
- Multi input measuring capability was added through a Julie Research scanner
- IEEE-488 bus capability was added via a Hewlett Packard computer interface.

Proprietary system software provided by Julie Research to meet Grumman requirements is currently in its third generation. The software is "user friendly", requiring no computer programming knowledge to prepare calibration procedures for discrete instruments. To date, over 8ØØ individual instrument models have had custom calibration procedures prepared. The average preparation time for such a procedure is less than 3Ø minutes, making it practical to automate "one shot" calibrations for instruments which may never be calibrated on the system again.

The system controller remains the Hewlett Packard 983ØA. It has, however, been updated with a number of Infotek ROMS. Program storage has been shifted from sixteen cassettes to one-half of a floppy disk. An Infotek FD9830 disk system has dramatically enhanced program access capabilities without requiring any software changes.

AUTOMATED OSCILLATOR, FUNCTION GENERATOR, PULSE GENERATOR CALIBRATION SYSTEM

A desire to improve Measurement Standards' "in-house" design and development capabilities has led to a system for calibration of oscillators, function, pulse and other waveform generators (Figure 9). This is an IEEE-488 bus controlled system composed of a Tektronix 4Ø51 computer, Comprint printer, Krohn-Hite 688Ø distortion analyzer, Racal-Dana 9Ø15 Counter and Fluke 8922A True RMS digital voltmeter. Programming and interfacing were done by Measurement Standards. This automated system can measure:

- Frequency
- Distortion
- Amplitude
- Frequency response
- Rise/Fall time
- Pulse width

Data sheets are prepared automatically (Figure 1Ø). Calibration times for instruments calibrated by this system have been reduced up to 75%. Further development of this system, including a new computer and floppy disk addition, will be completed in 1983.

AUTOMATED MICROWAVE CALIBRATION SYSTEMS

An automated system for calibration of microwave components and active microwave devices has been a goal of Measurement Standards for many years. The major drawback of all systems available until recently was a lack of sufficient dynamic range. A Wiltron system (Figure 11) utilized in Measurement Standards' Calverton, Long Island laboratory is a case in point. It is a broadband system controlled via an IEEE-488 bus by a Hewlett Packard 85A computer. While this sytem can handle the calibration of many microwave components, its approximate 6ØdB useful dynamic range rules out its use for high value attenuators, filter rejection and directional coupler directivity tests where a greater range is necessary. In addition, it cannot perform the calibration of active microwave devices such as signal generators.

The most recent addition to Grumman's complement of automated calibration systems does, however, fill the need for calibration of virtually all microwave components as well as active instruments. A Microtel Automated Microwave Calibration System (Fiqure 121 was installed durinq the past few weeks.

The Microtel System designed for Grumman provides the following capabilities:

- Attenuation measurement to 100dB from 10MHz to 18GHz
- VSWR measurement (usinq custom Wiltron bridges)
- Frequency measurement
- Power measurement
- Modulation measurement.

The heart of this system is a broadband programmable IF substitution receiver which is a direct descendant of the original manually operated Microtel GC-128Ø Signal Generator Calibrator. The GC-128Ø was created to meet Grumman's 1974 request to provide a self contained system to track signal generator attenuator linearity to -100dBm from 10MHz to 18GHz.

Preliminary figures indicate that calibration time for broadband microwave components can be reduced by up to 9Ø% using the automated system as compared to the previously used method of using multiple narrow band swept setups.

Signal generator calibration time reductions of 5Ø% to 75% are anticipated.

FUTURE AUTOMATED CALIBRATION SYSTEMS

Load Cell System

In-house development is currently underway to automate the calibration of load cells. This system will utilize a Fluke 172ØA computer for data collection and analysis.

RF Power Sensor System

Purchase of a Weinschel System II Power Meter Calibrator (Figure 13) will automate calibration of power sensors which currently is a very labor intensive task. Grumman's evaluation of this system showed a reduction of calibration time for a typical broadband thermoelectric type sensor from 16 hours to 15 minutes. This system is anticipated to be in service in mid 1983.

Oscilloscope System

Acquisition of a Ballantine Laboratories Oscilloscope Calibration system (Figure 14) is in process. The calibrator itself is the commercial version of the unit developed for the Navy MECCA program.

Record Keeping

Calibration time for many instruments has been reduced by automation to such an extent that in many cases it is exceeded by the handling and paperwork time associated with calibration. While an extensive computer system provides record keeping and tracking for the calibration system there are still areas where a considerable labor effort is involved. A prime example in Measurement Standards' operation is the point of input of information into the tracking system. Each item processed by the laboratories requires a minimum of two separate entries typed in through a terminal's keyboard. Over 1213,ØØØ such entries are made per year. Even a very low error rate in entering this information causes an administrative headache of major proportion.

Measurement Standards is currently implementing a bar code entry system to eliminate most manual data entry to the tracking system. The proposed work order which will accompany each instrucment will have that instrument's identify number encoded upon it in bar code. The code will be scanned by a reader wand as the instrument is received for service. A menu will be provided to allow scanned input of dates, repair and calibration times, technician identify, performance ratings, etc. This system is highly error resistant and should also significantly reduce terminal operator time. A mid 1983 operational date is anticipated for the bar code system.

Conclusion

Grumman Aerospace Corporation, through its Measurement Standards section, has compiled an outstanding record of successfully applying automation to the calibration process. The key ingredients for successful automation have proved to be careful selection of hardware and software, diligent oversight of system operation and most importantly a willingness to be innovative and creative.

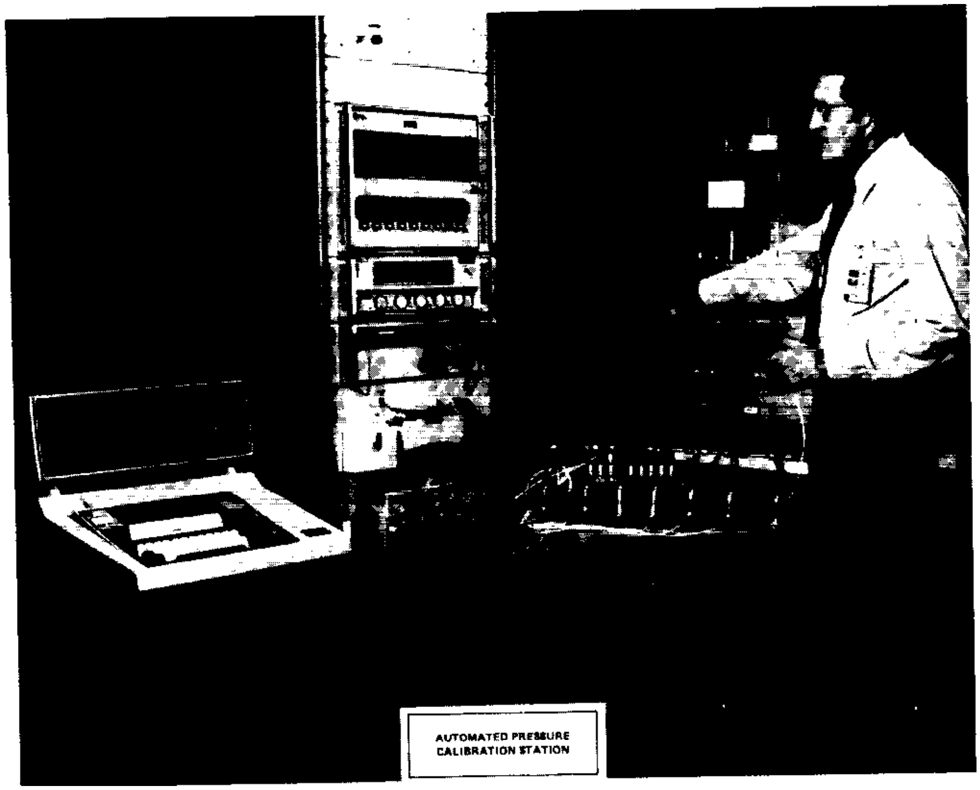


Figure 1 Automated pressure calibration system

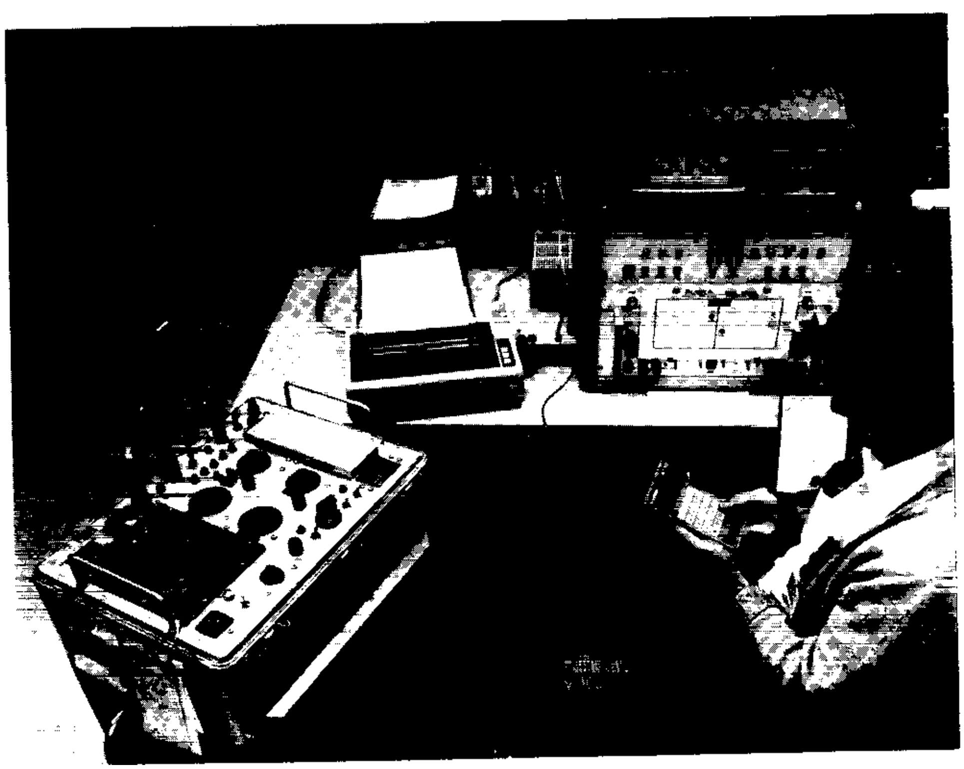


Figure 2 Automated air data test set calibration system

GRUMMAN AEROSPACE CORPORATION

CMSL CALIBRATION DATA SHEET CMSL

TTU 205
TEST SET, TEMPERATURE/PRESSURE

Procedure:C2733003 Tech:MS162 M S 62 Date:01-Sep-82

MFR CODE: KOA UNIT ID #:5224

STANDARD: RUSKA, AIR DATA TEST SET, MODEL 6000 II, #:162751G DUE DATE:16-DEC-82

STEP No.	STD FEET	IND FEET	CORR FEET	% of E.B.	STD KNOTS	IND KNOTS	CORR KNOTS	% of E.B.
1	-1000	-994	-6	40	75.00	73.80	1.2	80
2	0	-2	2	13	50.00	49.80	0.2	13
3	500	501	-1	6	100.00	98.70	1.3	87
4	1000	989	11	73	[illegible]	148.60	1.4	93
5	5000	4997	3	[illegible]		[illegible]	1.5	100
6	10000	9998	[illegible]				1.5	100
[illegible]	15000	14978						[illegible]
	[illegible]	[illegible]						

Figure 3 Data sheet - automated air data test set calibration system

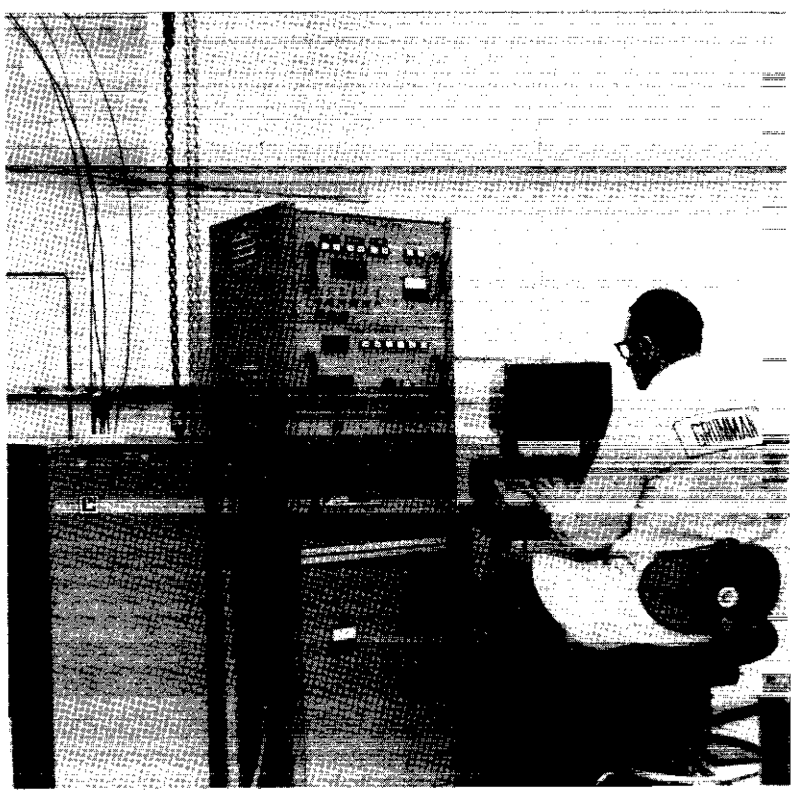


Fig. 4 Automated thermocouple calibration system

THERMOCOUPLE CALIBRATION
METHOD: TEST THERMOCOUPLE VS. WORKING STHNDHRD

****

CUSTOMER.................:STONE 8 WEBSTER

CALIBRATION DATE.........:8-3-82

THERMOCOUPLE I.D. NO. Ø5518

TYPE.....................:K

ISR TOLERRNCE: SPECIHL
AT OR BELOW 53Ø DEG.F = +,- 2 DEG.
ABOVE 53Ø DEG.F = +,- 3/8 OF 1% OF SET-POINT

HLL TEMPERATURES RRE IN DEGREES FAHRENHEIT

WORKING STANDARD	TEST	DEVIATION (STD - TEST)	LIMITS OF ISR TOLERRNCE	
2ØØ.2	2Ø2.1	-1.9	+2.0	-2.Ø
6ØØ.4	6Ø2.3	-^	+2.3	-2.3
1000.1	100[illegible]			-3.8

Figure 5 Data sheet - automated thermocouple calibration system

Figure 6 Automated dc-low frequency calibration system

GRUMMAN AEROSPACE - MEASUREMENT STANDARDS

FILE # 1038 MODEL: KEG191F- TAG: 98114M DATE:1/7/82

PART 1 0.2 VDC

STEP	DATA	INPUT	FREQ	ERROR	%RGE	%VAL	DIG	%ALL
1.01	+0.100006	0.1	0KH	0.0000060	0.0000	0.0070	3.6	60
1.02	+0.190004	0.19	0KH	0.0000040	0.0000	0.0070	3.6	25

PART 2 2 VDC

STEP	DATA	INPUT	FREQ	ERROR	%RGE	%VAL	DIG	%ALL
2.01	+01.90004	1.9	0KH	0.0000400	0.0000	0.0070	2.6	26
2.02	-01.90011	-1.9	0KH	-0.0001100	0.0000	0.0070	2.6	-83

PART 3 20 VDC

STEP	DATA	INPUT	FREQ	ERROR	%RGE	%VAL	DIG	%ALL
3.01	+001.1110	1.1111111	0KH	-0.0001000	0.0000	0.0100	2.6	-32
3.02	+002.2222	2.2222222	0KH	0	0.0000	0.0100	2.6	0
3.03	+003.3334	3.3333333	0KH	0.0001000	0.0000	0.0100	2.6	19
3.04	+004.4446	4.4444444	0KH	0.0002000	0.0000	0.0100	2.6	31
3.05	+005.5559	5.5555555	0KH	0.0003000	0.0000	0.0100	2.6	40
3.06	+006.6671	6.6666666	0KH	0.0004000	0.0000	0.0100	2.6	46
3.07	+007.7783	7.7777777	0KH	[illegible]	[illegible]	0.0100	2.6	51
3.08	+008.8895	8.8888888	[illegible]	[illegible]	[illegible]	[illegible]	2.6	55
3.09	+010.0007	10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	58
[illegible]	+011.1119	[illegible]						

Figure 7 Data sheet - automated dc-low frequency calibration system

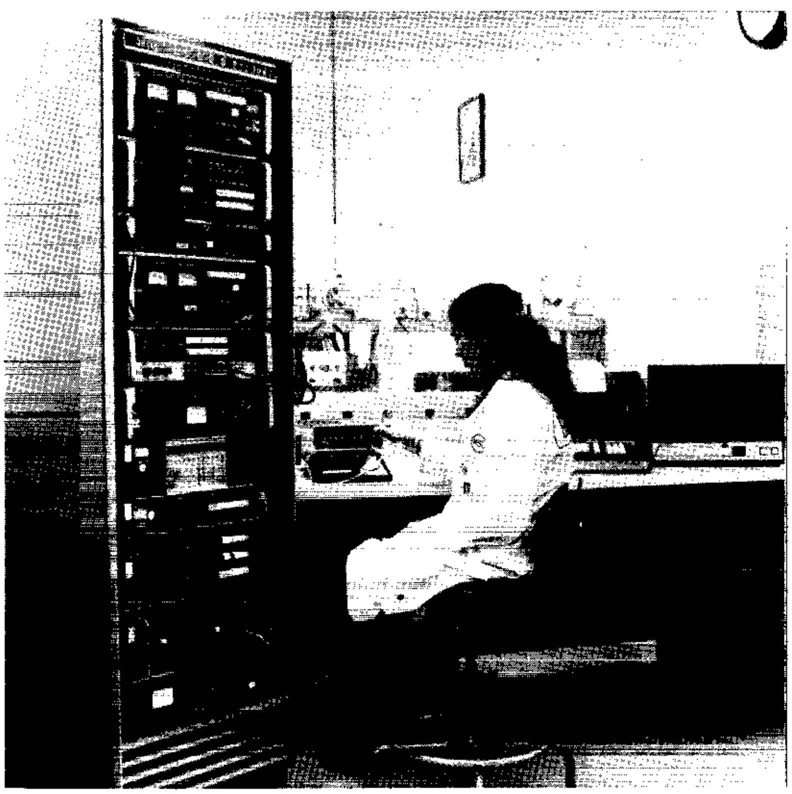


Fig. 8 Automated dc-low frequency calibration system-update

Fig. 9 Automated oscillator, function and pulse generator calibration system

GRUMMAN AEROSPACE CORPORATION
MEASUREMENT STANDARDS LABORATORY
BETHPAGE, NEW YORK 11714

REPORT OF CALIBRATION

MANUFACTURER......HEA	PROCEDURE NO.......1411005B
MODEL NO..........200AB	TECHNICIAN.........240
I.D.NO............59134	CALIBRATION DATE...121482

TEST RESULTS

TEST	FREOUENCY	NOMINAL	MEASURED	E/A CONDITION
FREQUENCY	4000.000HZ	4000.000HZ	3960.000HZ	-50.0% PASSED
FREOUENCY	8000.000HZ	8000.000HZ	8050.000HZ	31.3% PASSED
FREQUENCY	20000.000HZ	20000.000HZ	20020.000HZ	5.0'2 PRSSED
FREOUENCY	40000.000HZ	40000.000HZ	39560.000HZ	-55.0% PRSSED
FREQUENCY	20000.000HZ	20000.000HZ	19663.700HZ	-84.1% PASSED
FREQUENCY	2000.000HZ	2000.000HZ	1960.000HZ	-100.0% FAILED
FREOUENCY	200.000HZ	200.000HZ	190.000HZ	-250.0% FAILED
RESPONSE	1000.000HZ	0.000DB	0.000DB	0.0): PASSED
RESPONSE	100.000HZ	0.000DB	0.100DB	10.0% PASSED
RESPONSE	10000.000HZ	0.000DB	-0.120DB	- 12.0% PRSSED
RESPONSE	20000.000HZ	0.000DB	-0.39008	-39.0% PRSSED
DISTORTION	20.000HZ	0.000%	0.000%	0.0% PASSED
DISTORTION	10000.000HZ	0.[illegible]		16.6% PASSED
DISTORTION	20000.000HZ			[illegible] 8% PASSED
[illegible]RTION	40000.[illegible]			[illegible]ASSED

Figure 10 Data sheet - automated oscillator, function generator, pulse generator calibration system

Figure 11 Automated microwave calibration system

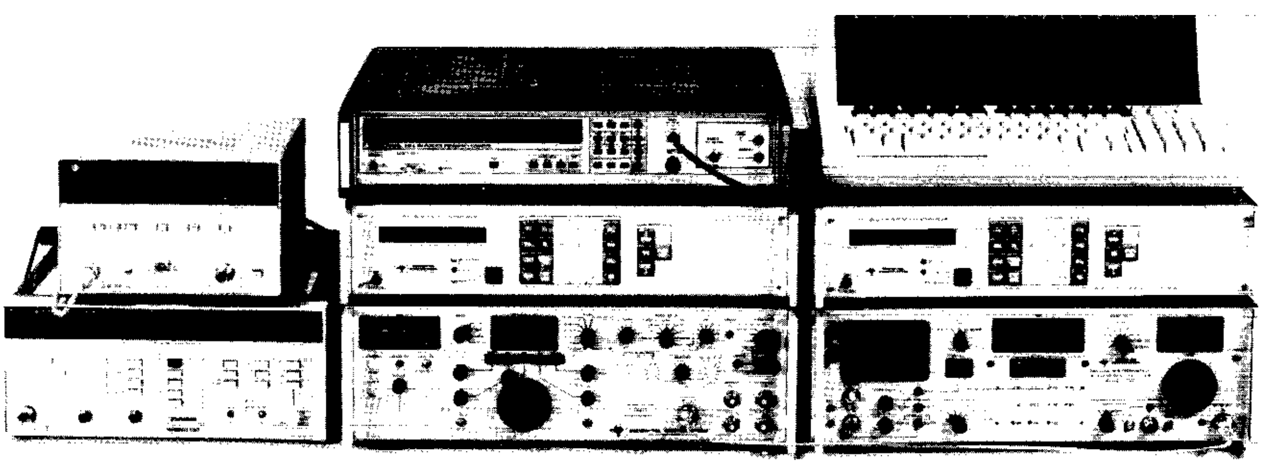


Figure 12 Automated microwave component and signal generator calibration system

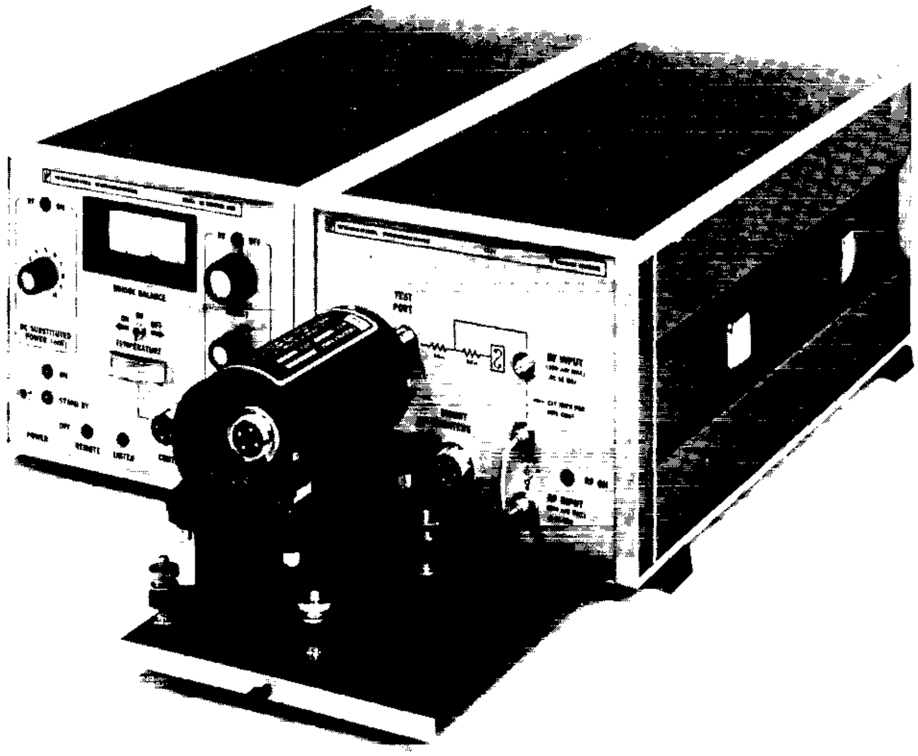


Figure 13 Automated rf power sensor calibration system

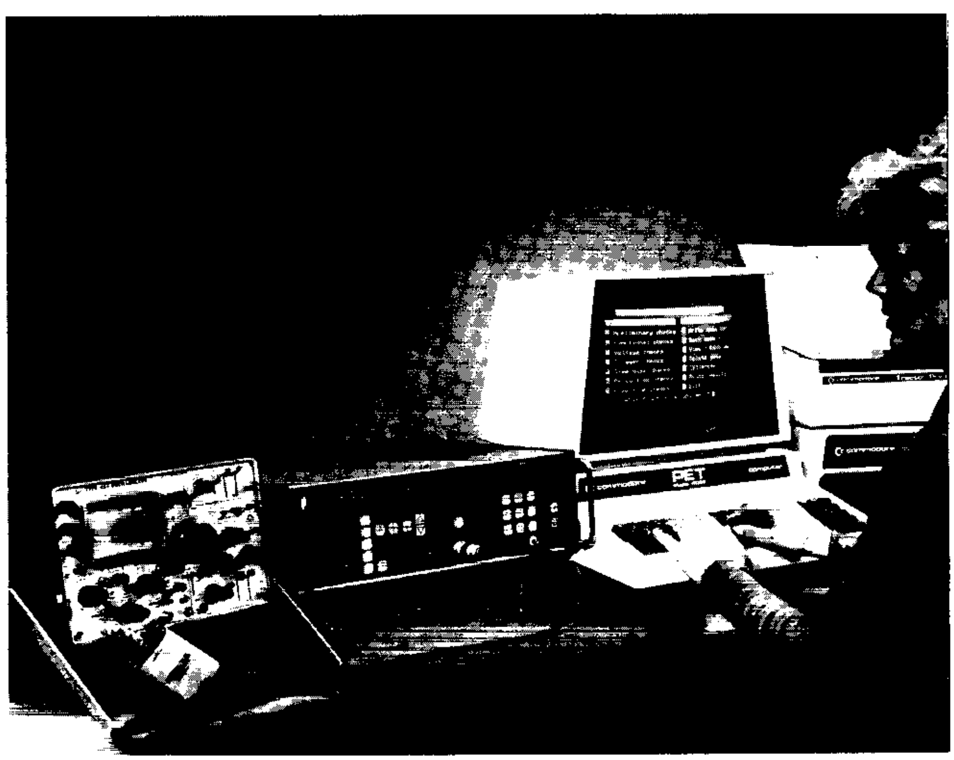


Figure 14 Automated oscilloscope calibration system

ATE SOFTWARE - A PRODUCTIVITY TOOL

Frank Sevean
Supervisor - Applications Software
Bendix Test Systems Division
Teterboro, New Jersey

ABSTRACT

The use of Automatic Test Equipment and its test software has entered into all levels of electronic testing and is growing. This is due to the cost savings which this equipment and software provides, especially when compared to manual testing methods and techniques. With electronic equipment becoming more complex per square inch of board real estate, more and more highly skilled technicians are needed to provide the proper manual support. Automatic testing does much to alleviate this problem but certain software elements could, if not properly identified and controlled, cause these savings to be less than anticipated.

INTRODUCTION

The widespread use of Automatic Test Equipment (ATE) throughout industry and the military services has resulted in substantial cost savings in the area of electronic testing. These savings are primarily due to the utilization of test program software to replace many of the time consuming and error prone operations previously performed manually. In order to benefit from these cost savings, however, certain initial trade-offs must be performed which must address the support costs of the various software elements inherent in ATE of all sizes. For the purposes of this discussion, it will be assumed that the initial trade-offs concerning the particular needs of the targeted units for which test software will be developed has been accomplished and the use of ATE has been found to be cost effective. This paper will address all of the software elements of ATE and examine the benefits afforded by these elements in performing the test/maintenance functions.

AUTOMATIC VS MANUAL TESTING

Comparing automatic and manual testing highlights more similarities than differences; especially when examining the functions required. A manual test bench or setup for a particular unit under test (UUT) consists of various power, stimuli and measurement devices, a means of electrically and physically connecting and disconnecting these devices at the UUT interface, a knowledgeable operator and a test specification or procedure.

An automatic test system is very similar in that it too consists of power, stimuli and measurement devices, a means of routing these devices to the UUT interface and a knowledgeable operator. The test specification is replaced by the test program for the particular UUT; in effect one type of software is substituted for another.

The difference between the two types of testing approaches becomes apparent when the operation of each is examined. During manual testing, a heavy burden is placed upon the operator since he must:

- Set all devices to the proper mode
- Perform all UUT interface connections/disconnections
- Make all pass/fail decisions
- Laboriously follow the test specification exactly

During each action required, there is the possibility for human error resulting in an erroneous test determination at best; damage to the UUT or test equipment at worst.

Executing the same test on automatic test equipment alleviates the operator from all activities except the initial interfacing of the UUT and starting the test program. The ATE controller assumes the major burdens of the operator and controls all of the devices as defined in the test software. The test is executed identically each time it is run and most, if not all, test result determination is contained in the software. All testing is done quickly and safely enabling the operator to complete his testing tasks with greater productivity.

OPERATOR SKILL LEVELS

Electronic equipment, especially in military applications, is becoming more and more complex and imposing higher demands on maintenance technician training and experience. Conversely, the services are having much difficulty in retaining experienced technical personnel and attracting the quantity of high quality recruits for training. The use of ATE at all levels of maintenance allows a reduction of the skill level required while boosting productivity. A good example of this was recently experienced by the U.S. Navy on the TRIDENT class submarine concerning the alignment of the Steering and Diving Position Control Unit (PCU). A controlled and monitored test was conducted where a highly skilled technician, very familiar with the tactical equipment, was required to perform the manual alignment procedures. This activity took four hours and ten minutes to complete; occasionally requiring assistance from another person. The same alignment was then performed by a virtually untrained operator using the Bendix Ship Control Tester - Organizational. The complete alignment was accomplished in a little less than forty-five minutes by having the operator simply follow the displayed instruction when adjustment was necessary. This complex task was simplified, accomplished faster and was performed by an untrained operator guided by the test software.

SOFTWARE ELEMENTS

Test programs do not operate in a void nor are they developed without the use of development and verification tools. While most test program set (TPS) development activities concentrate on the development of effective test programs; the identification and control of the other ATE software elements must not be overlooked. These elements will vary in type and complexity depending on the size and requirements of the particular ATE system.

The following is a list of general software elements existing throughout the entire spectrum of ATE:

- ATE Operating System
- Test Execution System (Executive)
- Support/Utility Software
- Instrumentation Software
- Facilitating Software

All of the above elements are vital for either the development or the execution of the test software. As such, each specific element requires control of its configuration and support personnel who understand the interrelationships between the elements. A revision to 'any of the above. listed packages, especially after field deployment of many test programs, could result in problems ranging from none to disastrous. The same statement can be made for revisions to the ATE hardware of course. The requirement for revisions in either the hardware or software systems would depend on the maturity of the systems to a great extent.

ELEMENT DEFINITIONS

The following is a brief description of the types of functions provided by each of these elements:

Operating System: This type of software is usually found in larger ATE systems and contains the control and service routines which brings the system to life. The functions provided generally consist of:

- Resource Management
- Peripheral Control
- File Management
- Text Editors
- Utilization Reporting System

The above list is certainly not all inclusive and depends greatly on the range of requirements for a particular ATE system. Any revision to an operating system must be carefully analyzed and implemented with a great deal of testing and under tight control.

Test Execution System: This system is often called the Executive and is found in both large and small ATE systems. In effect, the Test Execution System executes the test program and, in larger systems, will often utilize operating system functions. Some of the functions contained in this system are:

- Device Controller Routines
- Dperator Interface Software
- Test Mode Selection Software

In general, all the software necessary to perform the testing as defined in the test software; control of the stimuli, power and measurement devices, test result determination, etc. Due to the close relationship of the Executive to the test software, the probability of a revision causing a problem is very high. Any changes must be undertaken with great care.

Support/Utility Software: This is a catch-all term and generally refers to the software modules used for test software development, system maintenance and operator tools. Depending on the size and utilization of the ATE system, some of these functions could be imbedded in the Operating System or the Test Execution System. The support or utility software could consist of:

- Language Translators
- Test Language Compilers
- Automatic Test Program Generators
- UUT Simulators
- Software Debuggers/Monitors
- Emulators

The functions are used to develop and verify test programs on the whole. A revision to these types of software modules will generally have no impact on previously developed test software but could cause problems should the test program require changes.

Instrumentation Software: An increasing number of stimuli and measurement devices contain their own control and communications software. This is usually provided by the manufacturer of the instrument and is seldom, if ever, modified. The ATE developer and the end user generally have no visibility of this software. While the potential for problems is very slight, an instrumentation software change could cause field problems. Control, however, of this software is usually not available to the ATE developer and, subsequently, the end user.

Facilitating Software: This software is really the baseline upon which all of the other ATE software is developed. It refers to the language assemblers or compilers which are needed to develop the system elements. An example of facilitating software would be a FORTRAN or PASCAL compiler which would be used to develop a translator or test execution system. This type of software is generally very mature and, since it is primarily used for system development, contains very little potential for problems in the field.

SUMMARY

Test software can result in substantial cost savings in electronic equipment maintenance due to providing a means of achieving greater productivity. This productivity is achieved by the time savings accrued and the utilization of low or moderately skilled personnel. Control of the test software and the system software elements must be exercised in order to maximize the savings of any ATE system. Without the support of personnel knowledgeable in the software system and a structured change control procedure after field deployment, the possibility of expensive field problems will exist. Examining the various elements for a particular ATE system can highlight those modules whose change would cause high risk. Recognizing these risks and providing the proper control procedures will minimize costs and surprises.

SYSTEMS APPROACH TO AUTOMATIC
CERTIFICATION AND CALIBRATION OF ATE

Ronald Ruotolo
Grumman Aerospace Corporation

ABSTRACT

Major certification and calibration problems exist with sophisticated Automatic Test Equipment that contains extensive analog, video and RF test capabilities. Generally, individual instruments within such ATE require certification against a secondary standard located at some remote calibration facility. The remote calibration of individual instruments creates numerous problems and results in inefficient and ineffective utilization of ATE. Some of the more sever problems are:

(1) Excessive ATE down time due to instrument removal for certification and calibration.

(2) Damage to instruments and/or loss of instrument accuracy due to transporting or shipment.

(3) Uncertain ATE system performance specifications that bear no relationship to instrument calibration parameters.

(4) Unnecessary calibration of instrument parameters that have little significance at the ATE system level. Conversely, parameters that are important at the system level are often not calibrated at the instrument level.

(5) Unnecessarily high and costly traffic through a limited number of calibration facilities.

In summary, expensive ATE is often shut down for extended periods while its system elements are remotely certified to unrelated instrument specifications. The cost is high and the calibration turn-around cycle tends to be lengthy.

The proposed paper will address system approaches to providing efficient and practical automatic ATE field certification that solves the types of problems highlighted previously. The techniques that will be explored in the paper will consider impacts on:

- ATE System Hardware (particularly RF elements)
- ATE System Software including ATLAS and its associated Operating System
- Transfer Standards
- Calibration at the ATE/Unit Under Test Interface
- Traceability from System Performance Specification to Primary Standards
- Automatic Software Correction of Out-Of-Tolerance Conditions

Examples of current ATE systems employing various techniques will be discussed. The trend for next generation ATE systems will also be covered.

The fundamental theme of the paper will be to propose practical solutions to today's well documented problems with field calibration of ATE systems.

GAGE BLOCK CALIBRATION WITH COMPUTER ASSIST

Lloyd A. Carver
Physical Metrology Supervisor
SIMCO Electronics
382 Martin Avenue
Santa Clara, CA 95Ø5Ø
(4Ø8) 727-3611

INTRODUCTION

In the past we have had the same problems with repeatability on gage blocks as have many others. Among the steps we took to eliminate this problem was the initiation of a semi-automatic calibration program. The heart of this was to be a micro-computer. To this end we wanted a unit that would (A) Store data from our Standard Blocks, (B) Store data on each set of blocks brought in for calibration, (C) Store the tolerance for each block brought in for calibration, (D) Store the in tolerance or out of tolerance condition found on each block, (E) Determine whether or not a set of blocks must be down-graded, (F) Print a Certification for each block set brought in for calibration, (G) Measure each block for length, (H) Calculate parallelism for each block, (I) Perform calculations to determine if the block set in for calibration is within tolerance, (J) Close the measurement loop on the standard block to insure the measurement was good and determine the uncertainty of the particular standard block, (K) Store measurement assurance data for determining random uncertainty at any give" time.

CHOICE OF A COMPUTER

Since TRS-8Ø micro-computers were in use at SIMCO for several other automatic calibration areas, it was decided to use the TRS-8Ø with this program also. It was decided a 48k bytes of RAM with 2 floppy disc drives would be suitable.

SOFTWARE

The software is arranged into two separate discs. The Data Manager disc always resides in the Operating System drive. It contains the instructions for operation of the Gage Block Measurement Assurance System. The second disc is for the storage of data on the Unit Under Test (U.U.T.). These are generally broken down by companies. A separate disc is used for each major company to simplify future compiling of historical data. The Data Manager disc also contains the data used to generate the Certification and the Data Sheet for each gage block set.

This program has all the features of a commercially available data base management system. Figures 1 through IV show data entry forms as they appear on the screen.

This program has been made to operate with the minimum chance of mistake. Place the Data Base Manager in the appropriate disc drive, select the data disc for the company that owns the blocks, and at the touch of one button a menu is produced in plain English.

We will study the use of the program from the menu, Figure V. This will allow us to view the many checks that have bee" built into this system to eliminate errors.

CALIBRATING GAGE BLOCKS

Some of the work must be done before the first set of gage blocks come through the door. To start the system prior to the first set of blocks we must use <S>tandard set manager*. It must be remembered that anything in the computer memory will be lost when we go to anything followed by *, so be sure to save everything to the disc before going to <S> Figure VI shows the data from the standard gage block set that must be entered prior to using the program for measurement of gage blocks.

The material will be used to compensate for temperature variations at the time of calibration. The Last(L), (L-1), and (L-2) readings are the history of the deviation of your standard gage block.

Another step that must be completed prior to measuring the gage blocks is the standards information that will be used on the Formal Certification. Since specifications, calibration test numbers, date do re-calibration, etc., are not the same for all blocks to be used as standards, we enter "Standards Used" information in the order asked for in Figure VII. The *Note area is where we keep the NBS test# and date of test.

Following this we enter or <E>dit traceability test *, for the text of the statement of methods and uncertainty. As the methods change or uncertainty is decreased we will be able to edit this statement without going into the basic program itself.

After that we are ready to use the program on a set of blocks. If when we check the data'disc we do not find the set listed that we are about to calibrate we will go to <A>dd U.U.T. blocks. The dark border will appear around the Standard Set area of Figure I. Using the up-down arrows we will advance the Standard Set block size until it is at the same size as we wish to enter for the unknown set. If the size we want to enter is not in the Standard Set we will not be able to enter this block because we will not be able to calibrate it. When we find the proper size (they are stored numerically) we key in ENTER . At this time the dark border shifts down to the Unknown Set area of the screen and the size is entered in the Unknown Set area. For sizes less than 1 inch the parallelism tolerance and the + and - length tolerance is also automatically entered. The fields are opened for data entry in the unknown block serial number and type material. When all the appropriate information has been entered on this block, ENTER again and the dark border shifts back to the Standard Set for the next block. Upon exiting this mode all entries are sorted for size and put in ascending order by length.

If this particular set had been calibrated with this system before this time, we could have gone to the <U>.U.T. file handler. This would have brought up a screen as in Figure VIII. From there we could have gone into the mode to <R>ecall the particular set we were working on. From there we could have gone back to <C>hange U.U.T. blocks, to verify that all the serial numbers were still the same. Any changes or deletions may be done from this mode. Also from this mode, we may go the /C/heck mode.

When we key in the /C/heck, we get a screen as in Figure IX and the choices of <P>recheck or<F>ull check. In <F>ull we go through a series of truths as can be seen in Figure X. First we go through the comparator to make sure we still have the Standard of the same size in our Standard Gage block set. If not, all the information we have entered on that block prints out on the printer and the block is deleted from the list of blocks to be calibrated. If we do still have the Standard it compares the size and serial number of the block with the block before and the block after it in the memory. Since the blocks have all been sorted by size this will show whether or not there are any duplicate entries in the list. If there are, as before, it will print all the information and delete the duplicate from the list. If there are no duplicates, it will step on down the check.

The next check is whether or not there is anything in the serial number block. On blocks with no serial number we will have entered (NONE) so any with nothing in the serial number block will be an error. If a blank is detected it will wait on that space for the correction. After the correction is completed we must hit <ENTER> to continue. The next check is whether there is a C for carbide or S for steel in the material block. Any other entry or no entry will fault and wait for you to correct it. The next check is to verify there is a tolerance listed and that the polarities are correct.

The last check-of this sequence is to check the inputs on the Last Chk: block. This will only allow F, *, P, or a blank to be present, and the letters will only be allowed to be in the appropriate place.

In <P>recheck the same steps are down except there is no comparison to the Standards Blocks. This will be used whenever you wish to run a check except when the blocks have just been re-entered from disc.

After this we are ready for calibration of gage blocks. The first thing after cleaning is flatness. If the flatness is out of tolerance we must enter an<F>in the Last Chk: block in the <C>hange U.U.T. blocks mode. Then the blocks are placed on heat sinks for 24 hour soaking and all data in the computer is stored on disc using <U>.U.T. file handler.

When the soak time has been completed, measurements are made for length and parallelism. This data with out-of-tolerance information is input into the computer in the<C>hange U.U.T. block mode.

A formal certification, Figure XI, is then printed. First we do to the <T>raceability report, entering the temperature, humidity, date calibrated and date due. Then <C>ontinue is keyed in and the Standards listed as having been used for calibration are checked to verify they are proper standards. Next <P>rint is keyed in and the formal certification is printed. The <D>ata is keyed in, the paper aligned and <P>rint is keyed. The computer counts the number of blocks that were out of tolerance for (F) flatness, (*) length, or (P) parallelism and determines what percent of the complete set was out of tolerance. It then prints the data sheet (Figure XII). If the gage block set had 25% or more blocks out of tolerance, a statement is printed on the data sheet that the set no longer meets the grade for which it was bought.

At this time we would key in the <I>nitialize U.U.T. key. This would erase all data from the computer memory, losing everything that had not been stored on disc, readying the computer for the next set of gage blocks.

FUTURE

As you have probably noticed we have not talked about the <M>easure U.U.T. function of the Menu. The program has been developed and at the writing of this paper is in the finalizing stages of development for measuring the length of the gage block semi-automatically.

When we make the measurement we will first place our Standard block of the same size as the one to be tested between the contact points of the Gage Block Comparator. After the computer has read this block we will remove the Standard and place the block to be calibrated between the contacts, when the computer has read this point we will move the block to the second point and then the third. After reading the third point on the block being calibrated, the Standard Gage Block will be placed between the contacts to be measured again.

The first reading of the Standard block will reference the calibrator. As the computer knows the actual length, including deviation, we can use this as a reference point. The three readings taken on the block being calibrated will tell, by their average, what size the block is as compared to the Standard. Also by the deviation of the three readings, taken on different parts of the block, the computer can determine the parallelism of the block. The last reading is taken on the Standard to close the loop on the measurement and to determine, by comparison to the first reading on the standard, that no major problem has come up within the measurement system.

The computer will be keeping track of the deviation between the first and last reading on each set of readings made for a specific size. From this, standard deviation, or sigma, will be determined and evaluated for each Standard block individually. Other data, for Quality Assurance Management use, will be stored, compiled, and evaluated. With this we will be able to maintain historical records on the standard blocks.

In addition to all this, the <M>easure U.U.T. will increase the readability of the mechanical comparator from an interpalation of about .3 millionths to .001 millionths or better. As is obvious this will decrease the uncertainty by more than a half a millionth in reading the comparison in length between the standard and unknown block alone.

CONCLUSION

Repeatability has been questionable on gage blocks. With the introduction of the computer to our gage block measurement system we have been able to cut down the uncertainties that were causing the problem in repeatability. With the advent of the final phase of the computer program the speed with which a gage block set can be calibrated, increase in repeatability, and the decrease in uncertainties will be greatly enhanced.

```
                      Standard Set    M0352/E2
  Block size:    .010       Serial #: 5DHP       Chk: ...****

                              Unknown Set
  Block size:               Serial #:            Material:
                            Ptol:   S+tol:          S-tol:
                            Last reading:        Last Chk:

                             Measurement,
  Temp          Deg. c         Std.:             This Chk:
                               Unk.:
                               Std':

V-arrows move std. blocks (ENTER) adds to unk. set <@>Menu
```

Figure I

```
———————————— Standard Set   M0352/E2 ————————————
Block size:.......... Serial#:.......        Chk: . . .

———————————— Unknown Set    TEST/VAR ————————————
Block size:    .010   Serial #:              Material:
                      Ptol: 4   S+tol: +4       S-tol: -2
Changing block 1      Last reading:          Last Chk:
———————————————— Measurement ————————————————
Temp          Deg. c      Std.:              This Chk:
                          Unk.:
                          Std':
——————————————————————————————————————————————
V-arrows move blocks   H-arrows move cursor   .C.hk .D.el <@> Menu
```

Figure II

Traceability Report

```
-Header  --
 Unknown set --> TEST/VAR      Make: WEBER   Serial#: 323322
 Grade: 2 Property of:   SIMCO ScP: 44432 #/blocks --> 3

 - STATEMENT -( <E>dit from menu.)

-- Footer--.
 Std-1: 3-Ø352 Std-2: 3-Ø357 Std-3:        Std-4:
 Ambient temp: 23.4 deg.c        Recall date: 8/14/83
 Rel. humidity: 4Ø%              Prepared by: L. Foutche'
 Issue date: 8/14/82             Approved by: L. Carver

  <I>nput  <C>ontinue  <@  >Menu
```

Figure III

```
Standard Set    M0352/E2
Block size:   .010      Serial #: 5DHP       Chk: . ..****

Unknown Set
Block size:             Serial #:            Material:
                        Ptol:   S+tol:          S-tol:
                        Last reading:        Last Chk:

Measurement
Temp          Deg. c       Std.:             This Chk:
                           Unk.:
                           Std':
V-arrows move std. blocks <ENTER) adds to unk. set < @ > Menu
```

Figure IV

```
S569/Gage Block Comparator                                    12/13/82

- MENU -     <I> nitialize U.U.T.
             <A> dd U.U.U. blocks
             <C> hange U.U.T. blocks
             <M> easure U.U.T. blocks
             <T> raceability report
             <D> ata report
             <U>.U.T. file handler
             <S> tandard set manager*
             <E> dit traceability test*
             <@ >D.O.S.*
                                                 STD: M0352/E2
*U.U.T. block data in memory will be lost. UUT:
----------------------------------------------------- =GPIB= ------

                       Make selection
```

Figure V

```
Block-size:  ##.#######     Serial #:.......    Material: .
Ptol: . . .      S+tol: . . . .      S-tol: . . . .      Check: . . .
(L-2)reading: ....    (L-1)reading:.....  Last(L)reading:..
--------------------------------------------------------------------
(L-4)delta: ....          (L-4)date: mm/dd/YY
(L-3)delta: ....          (L-3)date: mm/dd/YY
(L-2)delta: ....          (L-2)date: mm/dd/YY
(L-1)delta: ....          (L-1)date: mm/dd/YY
Last-delta: . . . .       Last-date: mm/dd/YY
Delta-avg.: . . . .       3Sigma(u): . . . .          Note:........
```

Figure VI

```
CONTRACT#/ITEM#:  #-####
    DESCRIPTION:  ........................................
        SERIAL#:  ..........
        CALDATE:  MM/DD/YY
        DUEDATE:  YY/MM/DD
       ACCURACY:  ............................
          *NOTE:  ........................................  ..
```

Figure VII

DRIVE :1	SIMCO	M0013/E2	M0014/E2
SA003356	SB002256	S1003366	S1001483
SCØØ3356			

....

<R> ecall <S> tore <K> ill <@> Menu

Figure VIII

```
———————————— Standard Set    M0352/E2 ————————————
   Block size: ..........   Serial#: ........   Chk: ....

———————————— Unknown Set    V4123032 ————————————
   Block size:   .03125     Serial#:            Material:
                            Ptol: 4  S+tol: +4   S-tol: -2
   Changing block 1         Last reading:       Last Chk:

———————————— Measurement ————————————
   Temp          Deg.c      Std.:               This Chk:
                            Unk.:
                            Std':
————————————————————————————————————————————————
  <P> recheck      <F> ull  check <E>xit
```

Figure IX

LOGIC FLO!! DIAGRAM

GAGE BLOCK CALIBRATION

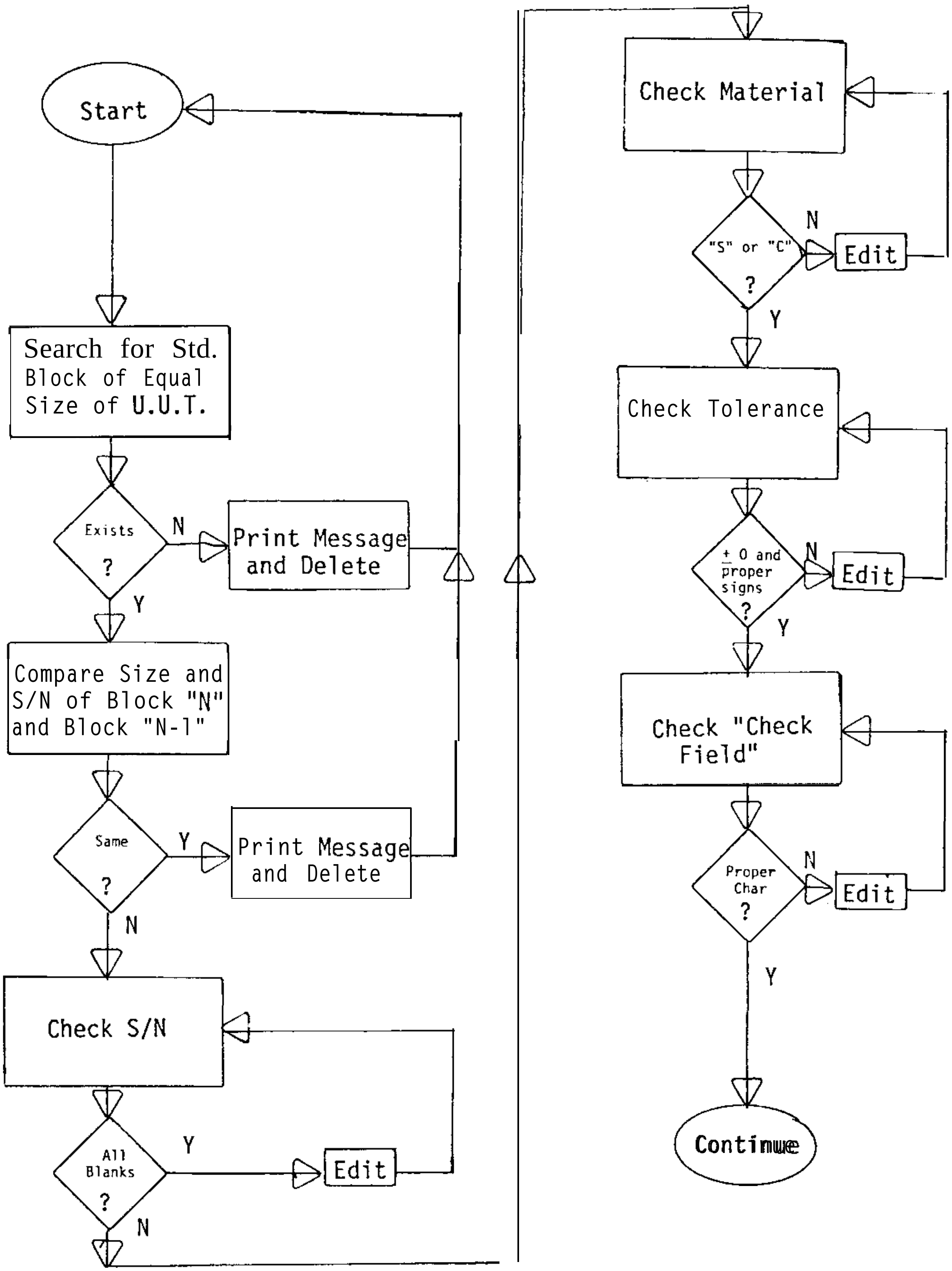


Figure X

simco
electronics

STANDARD CERTIFICATION and SERVICE LABORATORY

382 Martin Avenue, Santa Clara, California

REPORT
FOR
GAGE BLOCK SET

Mfgr./Model:Mitutoyo
Serial No: 97341
SUBMITTED BY

S I M C O
SCP. No: 31639

DATA

The tested gage blocks have been intercompared with a master gage block set that was calibrated traceable to the U.S. National Bureau of Standards.

The comparison was made by an automated system that minimizes systematic and random errors. A real time historic analysis is performed on the standard blocks each time it is used to verify their repeatability. This verification is a part of a general Measurement Assurance Program instituted at SIMCO.

The uncertainty of intercomparison varies with time and block size but it is in the order of 3 microinches per inch up to 4 inches.

For deviations from nominal size, and block qualifiers see the attached sheet which is an integral part of this report.

Standards Used	Serial Numbers	Certification Dates	Accuracies
Federal 1038-24 Gage Block Comparator	8208	3/4/82	(+/-) 1 u inch*
Federal E2-151 Gage Block Set	9343	1/20/82	Grade 2**
Mitutoyo No:157 Optical Flat Set	1003-0295	5/7/82	1 u inch***

*NBS test# 738/224984 date 5/1/81
**NBS test# 738/224984 date 5/1/81
***NBS test# 738/224131 date 11/21/80

Ambient Temp: 20.3 Deg.C **Prepared By:** L. Foutche'

Rel. Humidity: 39%

Date: 11/2/82 **Approved By:** L. Carver

Figure XI

CALIBRATION REPORT FOR ENGLISH GAGE BLOCK

SCP NO. 31639 GAGE BLOCK SET S/N 97341 Grade 3 No. of Blocks 81

Block size inches	Dev. in.	I.D. No.	Note	Block size inches	Dev. in.	I.D. No.	Note
.0500	-1	81247		.140	-6	800222	
.1000	+5	790110		.141	+2	800092	
.1001	-3	800108		.142	-3	801217	
.1002	+1	801080		.143	-3	801113	
.1003	0	801344		.144	0	801112	
.1004	+2	800122		.145	-3	801120	
.1005	-2	801037		.146		803112	
.1006	-2	801027		.147	-5	800377	
.1007	-3	800105		.148	+1	801104	
.1008	+2	801011		.149	0	801135	
.1009	+2	800344		.150	-5	791041	
.101	+1	801241		.200	0	770418	
..102	-2	800225		.250	+1	761365	
.103	0	800131		.300	+2	800326	
.104	-1	801040		.350	-2	800119	
.105	0	800310		.400	-3	800222	
.106	-3	801483		.450	+4	800245	
.107	-1	801426		.500	-3	800448	
.108	-4	800249		.550	-1	800274	
.109	-2	801062		.600	0	800051	
.110	-3	801239		.650	+4	800417	
.111	-3	801230		.700	+1	790076	
.112	-2	801052		.750	+3	800428	
.113	-1	801135		.800	-3	800409	
.114	-4	800084		.850	+1	800370	
.115	-7	780204		.900	-2	800092	
.116	-2	800322		.950	0	790279	
.117	-2	800042		1.000	+3	800244	
.118	-2	800238		2.000	-8	80098	
.119	-1	801371		3.000	-7	700218	
.120	-3	801330		4.000	-4	8 0 0077	
.121	-1	801434					
.122	-1	800141					
.123	+1	801445					
.124	-5	801118					
.125	+4	790222					
.126	-5	790097					
.127	0	801316					
.128	0	800324					
.129	-7	800123					
.130	-5	801346					
.131	-7	800214					
.132	-3	751140					
.133	-4	800149					
.134	+1	801092					
.135	-2	800161					
.136	0	801245					
.137	-7	800302					
.138	-4	801486					
.139	-3	801425					

Note: Does not meet tolerance for:
(*) length
(F) flatness
(P) parallelism

Figure XII

ACCURACY AND AUTOMATION IN WINE PRODUCTION

Larry E. Brink
Director of Winemaking and Blending
Paul Masson Vineyards

The wine industry, over the past decade, has made revolutionary advances in the application of science to the farming of grapes, fermentation technology, and preparation of wines for bottling. However, we cannot explain wine making in a completely scientific manner since neither the chemical composition of the grape or of wine is fully known.

We at Paul Masson are continuously applying the latest technologies in our production process so that consistent quality fine wines will always satisfy our customers expectations.

VINEYARD TESTS

Before any grapes can be processed, various test factors are considered in the vineyards to determine the correct time and method of harvesting which will ultimately reflect in the style of the wine produced. Grape maturity are measured by the analysis of sugar concentration, total acid concentration and pH measurement, along with general non-measureable observations of fruit and vine conditions.

To measure grape maturity we first take a statistical sampling of each vineyard by grape variety each week. This sampling, can often result in misleading results because of variations of grape maturities from vine to vine and even within the same vine. To overcome this sampling problem, our final sample consists of actually a small scale harvest of the vineyard which will finalize our decision to harvest or not.

These grapes are crushed and the pulp solids removed by centrifugation in the laboratory. The juice is analyzed for total sugars by refractometer or hydrometry, for total acid by titration with a strong base, NaOH, to an end point at pH 8.2 (phenolphthalein indicator solution), and for pH by pH meter. It is important for the winemaker to have a thorough knowledge of the composition of grapes to be harvested because the composition and quality of the finished wine depend largely on the proper maturity and condition of the grapes.

WINERY TESTS

Once grapes begin to arrive at the winery, each truck load, is sampled and the following tests are performed before processing begins.

1.) MOG (Material Other than Grapes)

    Example: leaves, canes, debris less than 3% by weight acceptable.

2.) % Rot - Substandard grapes will have moldy or rotten grape bunches. A percentage of moldy or rotten grape bunches will be determined by visual sorting.

3.) Sugar concentration by hydrometer.

4.) Total acidity by titration.

5.) pH by pH meter, in biological systems the pH is often of greater significance than the total acidity.

6.) Temperature of each load is measured. Cool temperatures are preferred.

The grapes are then crushed into tanks where the more honogeneous juice is again analyzed for sugar, acid, pH and temperature. From these results along with the understanding of the wine style desired, the juice is clarified and innoculated with yeast culture, or in the case of red and rose varieties left in contact with the skins and innoculate.

The fermenting juices are then tested daily for the following:

1.) Sugar concentration by hydrometer to monitor the fermentation conversion of sugar to alcohol.

2.) Temperature to monitor the rate of fermentation, desired between 50° - 65°F for white and rose wines and warmer for red wines.

3.) Tasting - The organoleptic evaluation of fermenting juices is performed daily to monitor the fermentation and detect any defects as early as possible. In the case of red wines the decision to separate a wine from its skins is based on taste and tannin level.

4.) Color - For rose wines the color is measured by the change in absorption at 420nm on a Bausch and Lomb Spectrophotometer. The color is not measured on white or red wines, only visual observations by the winemaker.

Once the alcohol fermentation is completed, the wines go through a series of "racking" to decant or separate the wine from the insoluable solids which remain after fermentation. Each tank of wine is being tasted daily to monitor its quality. Finally, the white and rose wines are clarified by centrifugation and/or filtrations. The red wines are generally clarified by allowing them to settle naturally with gravity. Each wine variety and/or tank is clarified differently in terms of method or timing, dependent on the style of wine to be made. These are decisions of the winemaker. Some wines, usually red wines, are put through a secondary bacteria fermentation to reduce acidity, called the malo-lactic fermentation. Some wines will have additions of "fining" agents of bentonite, gelatine, silicon dioxide and sulfur dioxide to further clarify or stabilize their condition.

The wines next begin their aging and blending programs, which vary, dependent on the style of the final blend to be bottled. Generally white and rose wines are always aged cool, 45" - 55°F, only in stainless steel for six to eighteen months before bottling. The purpose being to hold the freshness and aromatic characteristics in these wines while preventing oxidation. Red wines have aging programs which consist of stainless steel, redwood tanks and oak barrels for various time periods dependent on the desired style of the finished wine.

Once aging and blending is completed the wines are prepared for bottling. Each tank of each blend is tasted for quality and consistency. A "complete analysis" is performed at this time to satisfy in-house specifications, as well as to comply with government regulations. The "complete analysis" consists of analysis of alcohol, sugar, total acidity, volatile acidity, oxygen, carbon dioxide, sulfur dioxide, pH, iron, copper, malic acid, lactic acid, and stability to heat and cold storage.

Our alcohol concentrations are determined by gas chromatography method. The gas chromatography is calibrated with a National Bureau of Standards certified alcohol-water solution, and gives results reproducible to Ø.1% alcohol. The alcohol concentration legally has to be within ± 1.5% of the stated alcohol on the label. The alcohol concentration contributes significantly to any calorie claim made on the label, in the case of Light wines.

During bottling, fill volumes are determined by gravimetric method and all inventory is controlled by computer.

By now, you can understand that the production of wine is a natural *event* carried out mostly by Mother Nature and only guided by the winemaker. The accuracy and automation in wine production is not highly technical compared to other industries, but the application of modern technology in instrumentation and process equipment has taken place. For this reason the wines produced today are of better quality and more commercially salable than they were only thirty years ago.

Enjoying The Pursuit of Quality By Operating a Small Winery

Reinhold Banek and Dennis Bassano
Co-Owners of Grover Gulch Winery
7880 Glen Haven Road
Soquel, CA 95073
(408) 688-4335
(408) 475-0568

ABSTRACT

Concern for quality in producing premium red wines is a foremost objective. The road to developing a winery is strewn with obstacles, trials and pitfalls. The authors take the readers through the whole process from applying for governmental permission to marketing the finished product.

Once the decision has been made to establish a winery, the first order of business is to acquire the Bureau of Alcohol, Tobacco and Firearms application forms. Their stamp of approval is essential if one is to operate an official and legal winery. Once we had retrieved the fat package of forms from the mailbox, we had that sinking feeling that we might be getting in over our heads. Our suspicions were certainly confirmed once we opened it, and leafed through page after page of forms and questionsthat we could hardly even read or understand. We were tempted to call our lawyer for help, but being stubborn, we thought that we could at least give it a try. We got ourselves a glass of wine - that's what it's all about, right? - and sat down with the task.

As a start, each and every sheet requires your name with most needing your address as well, and so having written that much in, we were on our way. After we had completed all that we were capable of, it was obvious that we needed some help, and free help was available at the heart of the problem, the BATF Office in San Jose. For those of you who don't have a mental image of a Bureau of Alcohol, Tobacco and Firearms (BATF) Agent, I'll try to create one. They are an enforcement arm of the IRS, the "T" Men, the "Revenooers", who beat the bushes in the back country trying to bust "Snoopy Smith, and his neighbors for making moonshine. That was one of our visions, but actually the people there were very nice, as regular as can be, and trying hard to help us. One of the agents there showed us a typical application package, answered all of our questions and gave us the final bit of understanding needed to finish. We mailed in the forms, received an initial acceptance and made arrangements for a BATF on-Site inspection. In a remarkable short time our final approval arrived. We were an official bonded winery, and we were ready to make wine, or so we thought.

Just to be on the safe side, we checked with the State Alcoholic Beverage Control Office to see if we needed their blessings, which indeed we did. We filled out more forms, paid our fees and were duly fingerprinted which constituted our application for a liquor license that would allow us to sell our wine. Last, we thought, but not least was the county level approval in the form of business license, registration of fictitious name statement, and as it turned out, a use permit. We wereworried but there was no turning back now, as we had already crushed our 1979 vintage, and the wine was in the winery. Approval was possible and we got to thinking that we might be home free, but there was another surprise coming. Some of the neighbors panicked at the thought of having a winery in their neighborhood, and they blocked out approval. We had begun our approval process at the Federal Goverment level and we had worked our way all the way down to the grass roots. The concerned neighbors were invited to the winery for wine, cheese and to share our dreams, and we won them over. By the terms of our use permit we are restricted to the production of 5,000 gallons of wine per year, and tours and tasting by appointment only.

We were now a bonded winery with every kind of approval we could imagine, and we were making wine! Actually, if the whole truth were to be known, we made our first wine in 1969. Our first winery building, which was also Dennis' old barn, burned down along with our '69 vintage wine, and so we were forced to build another. It was sort of a rehabilitated chicken house that we reconstructed amongst the trees. We made some nice wine in that little shack, and we also made some "not-so-good" wine, some discoveries and mistakes and generally paid for our winery education with hands on experience. By 1977, we had outgrown our Little Shack and built what we considered to be a huge modern winery, which was to become part of our bonded winery.

You may be wondering what sort of equipment we used and how we found it. For the first couple of years we fermented in plastic lined cardboard drums and borrowed a small basket press from a friend down the road, and when we outgrew that operation, the same neighbor sold us his crusher and big press.

The press seemed giant at first, but as our realities, capabilities and capacity expanded, we grew into our press size and eventually grew out of it as well. In 1975 and 1977, we borrowed a crusher-destemmer and a fermenting tank from a winery friend and crushed 2½ tones each year.

One day, when we were visiting a scrap metal yard looking for a stainless steel pump, we spotted a huge old tired crusher-destemmer. Upon inspection, it seemed too big and too worn out, but the owner of the scrap metal yard was an old friend of Dennis' grandfather, and a deal was struck that we really couldn't go wrong with. Before we even realized what we had done, that big devil was on our truck and we were on the road home not even knowing how we were going to get it off. It was disassembled and sent to the machine shop with $200 to get its' roller shafts turned and fitted with new bushings. After a fair amount of welding and grinding, head scratching and drinking beer, modifying and painting, we had put together a functional machine at a fraction of the cost of a new one.

Other winery hand-me-downs are probably the best source of reasonable priced equipment. We purchased two of our fermenting tanks new, but the third tank bought used at one third the price of new ones works just as well. The most recent acquisition was our second hand labeling machine. Seeming functional, it still took a fair amount of cursing and head scratching, phone calls and adjustments and even a couple of panics to get it to put our labels on the bottles.

Another source not to be overlooked is ones' own imagination and special skills. We use our practical skills to build all of our own buildings, do plumbing and electrical work, build barrel racks and fabricate just about any labor saving gadgets we might dream up. One of our proudest "built from scratch" tools is a barrel washer that works great and saves us hours of barrel washing time and work.

We are now down to the part of the story where we actually make wine. We have all our equipment here, a building to make the wine, some expertise, but now we need fruit.

Some wineries grow their own grapes or at least part of their grape needs, but mostly farmers grow grapes and wineries buy them. We buy all of our grapes, getting them somewhat here and there, wherever we can find the high quality we like. Our first choice is grapes from old vines that are grown without the benefit of irrigation. You may not believe this, but the secret to making good wine is to start with good grapes and make a minimum number of mistakes. Really good wine cannot be made from mediocre grapes. Consequently, we are always on the lookout for available, high quality red grapes.

Wine quality control begins in the vineyard. We're interested in checking out the overall condition of the wineyard. Start with the not so subtle things like are the weeds taller than the grape vines? That's not to say that if there are few tall weeds the grapes will be bad, but that is the type of indicator to start with. Generally, the overall picture of the vineyard is one of beauty and sometimes it's even overwhelming. Visiting the vineyards is one of our favorite aspects of winemaking. But how does the vineyard really look? Have the vines been cared for? Do they look healthy with lots of nice green foilage, grapes hanging down in nicely developed, clean, uniform bunches? How old are the vines? Have they been irrigated? How do they taste?, Oh yes, we get to taste. We start tasting thr first grapes we see, as tasting is the most important of the field tests. If the grapes taste good in your mouth, there is a good chance that the wine will also taste good in your mouth. This is, of course, an over-simplification, but the attitude is correct.

Our main field tool other than our senses of sight, smell and taste is the hydrometer. We use a hydrometer instead of a refractometer because the sample needed to flat the hydrometer gives a better overall picture, as it includes lots of berries. If the grapes have a good acid-sugar balance in our mouth and the hydrometer reading is 22% sugar or a little more, the" the fruit is ready to pick. We try to buy grapes with a high acid content in order to make the style of wine that we like to drink. Government quality control allows wineries to add acid or any of five pages of chemicals to grapes or wine to compensate for deficiencies or effect changes We've chose" to keep our additionsto a bare minimum adding only yeast culture, malo-lactic bacteria culture and bi-sulphites. This puts us in the category of being somewhat old fashioned and making more-or-less "handmade" wines.

After talking to the grower, seeing and tasting the grapes, we must make a judgement as to whether we can make a satisfactory wine from those particular grapes. This is a difficult judgement and we are not always perfectly correct. It is one of the most challenging, exciting and educational aspects of winemaking. Once these subjective qualitative judgements are made in the vineyard, the rest is just business and timing. The growers try very hard to make their product available to you in such a way as to accommodate your special needs. Scheduling for the winery is as important and difficult as it is for any business. For us, it is doubly important, as both of us work full time at other occupations.

All of the grapes in a given area tend to get ripe about the same time and the growers like to get them out as quickly as they can after they are ready.

We have only three fermenting tanks, so we can ferment only two or three batches at a time. The picking of the grapes for us must be scheduled to coincide with having a" empty tank. To maintain top quality, we like to get the grapes to the winery and crushed, as soon after picking as possible.

For simplification of grape handling, we have evolved a system using our own trailer and empty boxes are take" to the vineyard and left there. The grower picks directly into our boxes and puts them back on the trailer. We drive over to the vineyard, hook up the loaded trailer and tow it back to the winery. You can well imagine that it doesn't often work out like that, but it still works better than most small winery methods we have see".

When the grapes are in transit, our spirits are high, as are worries about rain, heat, cold weather, too much or too little sugar are behind us, at least for this batch. Barring mechanical failure or interference from the highway patrol, the grapes will make their way to the winery and to the "crush".

The "crush" is the process of breaking the berries but not the Seeds, separating them from the leaves and stems, and delivering the result into the fermenting tank. I know that all of you thought that we had to do that with our feet, but we accomplish it by dumping the fruit into the top of the big crusher-destemmer, that we discussed earlier, and the crushed fruit comes out the bottom into the fermenting tank. With three people, and our present System, we can crush two tons of grapes in thirty minutes or less. That makes crushing one of our more minor labors. Once theberries are crushed and in the fermenting tank, the fermentation process is about to begin.

There is a difference of opinion among winemakers as how best to initiate fermentation. It is possible to ferment with just the natural yeast that is on the outside of the berries, or one can add any number of commercially prepared yeasts. The method that we have chosen is to add a culture thatwe have prepared from a liquid yeast culture, sugar, water and yeast nutrient. We buy the liquid yeastculture from the wine lab, and have chosen one thatmaintains good color and fruitiness. If we have our culture prepared and ready to use, we don't feel it necessary to add a bi-sulfite sterilantto the crushed fruit to suppress the natural yeast. The inoculant that we add has such a superior number of yeastcells that it begins quickly and accounts for the bulk of fermentation.

The temperature and sugar content are checked twice daily during the fermentation process. We also pump the wine over the floating skins, whichis called the "Cap", in an effort to extract the most color possible from the skins. When the sugar is down to about 5% (5 degrees brix), we add the prepared liquid malo-lactic culture. This starts a secondary fermentation with the breakdown of malic acid and it's conversion to lactic acid. This would probably take place sometime anyway, but by adding a cultureit is encouraged to go through the process at a more optimum time. If the wine goes through malo-lactic in the bottle, it will result in spoilage.

When the hydrometer reading is zero, all of the readily available sugar has been converted into alcohol and the real active fermentation has ceased. The wine 'then has been with the skins as long as it is safe to leave it, and it is now "press time". It has taken us somewhere between seven and fourteen days since the crush to get to this point.

Only the cap on top of the wine and the seeds in the bottom of the tank need to be pressed. The other two-thirds of the volume is liquid and is merely pumped. Press time means a late night for us unless it comes on a weekend. When the wine is ready, we have to get ready and So we do it after work. With the barrels ready and in place on the rank, we pump the available wine directly into the barrels with the same pump that we've been using to pump over the cap. When there is no longer enough liquid in the tank to keep the pump primed, the tank must be emptied into the press. The skins and seeds are called "pumice" at this stage and are simply shoveled into the basket of the press. Lucky for our aching backs we were able to trade our old hand crank press in on a bigger old electric powered one, and after a minor rebuild, it works like a champ. We just load it up, turn it on and have a beer, watch the pump, don't overfill those barrels, clean up and get ready for dinner.

This is a good place to fill in Some of the blank spaces in our winemaking philosophy. First and foremost, we try to make the kind of wine that we most like to drink. We make only red wines in a style we call "California-Italian" wine. That is in contrast to what we call "California-French" wines. By our over simplified definition here, a California-Italian wine is one in which the major influence is the fruit itself with very little barrel influence. The oak influence does add to the wines' complexity, but it also masks its'good qualities as well as its' flaws. Our winemaking style allows us to use used brandy barrels, which have been scraped down to new wood. These barrels add only an incidental oak taste, and allows the wine to stand upon the feet of the grapes that went into its' production.

Back to the winery, let us say that all the wine is in 50 gallon barrels, sitting happily on the racks with gas locks in place to allow the Secondary fermentation gases to escape without the wine being exposed to contaminants in the air. If you are only making a single batch of wine, then this is a time you can relax as the big push is over. Otherwise, of course, you are still driving to vineyards, making phone calls, fixing boxes, crushing Some grapes, pressing others and generally trying to keep on top of it all. For the sake of simplicity, let us say the wine is safely inbarrels and we've got time to discuss what we are going to do now.

At the time we put the wine into the barrels, there were a lot of solid particles in suspension, particularly in the wine coming out of the press, and we've got to have it out of our finished wine. A sound wine will generally become brilliantly clear by itself during its' aging process, as the particles naturally settle out. The process can be hastened by fining or filtering. Fining is a process where an agent is added to encourage the fine particles to form larger particles and settle out. We avoid fining and filtering when it appears that we can clarify the wine by "racking" along. Racking is the process of removing the clear wine from off the top of the sediment. We prefer racking to fining or filtering because those processes seem to remove too many good things from the wine along with the particles. Our approach is an added amount of work as the wine must be handled many move times, but we believe the end product justifies the added trouble.

We try to rack the wine the first time within two weeks of pressing. The wine quickly drops the bulk of the Suspended solids and these first Solids are the most harmful. Spent yeast cells along with skin and stem particles will impart a characteristic negative taste to the wine if allowed to breakdown in the bottom of the barrel. The taste is rather bitter, muddy taste, quite the opposite of a clean wine. Because we don't like a heavy oak tannin taste in our wine, it is especially important for the wine to be as clean as possible. We rack for the second time one month after the first, again in two months, again in three or four and with this last racking, the wine has gone into the barrels that it will live in for the next two years or until it is bottled. Granted, our approach is "old fashioned", but it does produce a wine that we enjoy.

Now that the wine is comfortably in the barrels, where it will age, we can get into an explanation of the laboratory chemistry that goes into our production. We attempted to set up a lab to do our own testing and set about to learn the necessary methods and techniques. We gave it a real try, but after getting results we didn't trust, we re-evaluated and found the cost of having our lab work done outside did not warrant the trouble and expense of doing it ourselves. Actually, we were veryrelieved.

The tests that we need to have done, and a simplification of the methods used are as follows:

1. Amount of alcohol by volume. This is important mainly because the amount of tax paid on wine is relative to the amount of alcohol. For winery purposes, the potential alcohol is read off the hydrometer before fermentation even begins. Accurate determination is made using an ebulliometer. "Alcoholic solutions boil at lower temperatures than water, and ebulliometers determine differences in boiling points, which are referred to tables or sliding scales to find the corresponding percentage of alcohol" 1.

2. Total Acid. Acid is expressed in terms of grams per 100 ml. It is determined by adding a phenolpthalein solution to the wine sample and titrating with a sodium hydroxide solution to a colored endpoint. The amount of acid is calculated from the amount of titrate solution needed.

3. Free and total sulphur dioxide. Determination is made by adding sulphuric acid to the wine sample and titrating with iodine using a starch indicator. It is titrated to a colored endpoint and the amount of sulphur dioxide is calculated from the quantity of titrate solution used. Sulphur is used in wine to inhibit oxidation and spoiling.

Actually, we made wine for 10 years without doing any lab testing at all. That's a relatively bad gamble when there is so much money invested. However, with or without the services of a lab, the non-lab checks are valid and important and should be conducted on a regular basis. The main test involved is no hardship at all, as it entails tasting the wine. If the wine is clear, brilliant in appearance, ruby to garnet in color without any browning, smells clean, vinous and fruity and tastes like we think it should, then we are truly on the right track. If this test is run regularly and often, any problems will probably be noticed in time to avert serious problems. Most potential problems are avoilded by keeping the sulphur dioxide content at the proper levels and, of course, keeping all barrels absolutely full at all times.

When the wine has reached the ripe old age of three years, it is usually ready to bottle. If by chance we have a wine that is very high in acid or shows great potential then we might consider holding it in the barrel for some additional time. At bottling time, we raise the free sulphur dioxide level to about 40 parts per million to carry the wine in the bottle until it *is* opened.

As winemakers, most of our worries are over once the wine is in the bottle. We hold our wine for at least six months of bottle age before releasing it for sale. The reason for this is because of the quantum improvement that it makes in those first six months. Immediately after bottling, the wine is bruised from handling and we feel it is a shame to drink it before it has begun to reach its' potential.

I hope that by now most of you have gotten into the romance of winemaking and have enjoyed the respite from the hastles of making wine under the watchful eye of government. We'll try to ease out of the romance here, and back into the day to day realities of keeping them informed of our activities. I suppose that there are some rare people who like keeping records and filling out forms and sending them in at the proper time. If you know someone like that, we have just the job for them. You can probably tell by the attitude here that paperwork is not our forte'. It is one of our chores and I guess that is the way in which we deal with it.

We have Federal and State monthly forms to file which are a record of our months activities. This information must be physically verifiable should we have a surprise inspection by the BATF. It is sort of like the threat of having your taxes audited by the IRS. Also, there are the federal wine tax payment forms to be compiled and sent every two weeks, the state wine tax every month, the sales tax payment each quarter, the Food and Agriculture Forms and tax yearly along with income tax and all of the various license fees. The "Big Brothers" try to watch wineries pretty close.

In addition to the formwork related to taxes, there are the records required for qualitative verification. We must be able to prove that the wine in a bottle labeled Cabernet Savignon is indeed Cabernet and not too much of other varieties. This starts by showing that we purchased enough Cabernet grapes to produce the number of gallons of Cabernet wine that we have on hand and that we bottle that same amount of wine with Cabernet labels on the bottles. Need I say more?

It is certainly a fine feeling when people taste our *wine* with enthusiasm and give us positive feedback. We have beentastingthe wine all along and hopefully have a realistic evaluation of it, but the positive reinforcement is gratifying. It gives a person that warm feeling like when all of the pieces of the

[1] BATF, part 240 of Title 27, Code of Federal Regulations.

puzzle have been put together and the picture presented was worthwhile. It is a wonderful feeling to see that you have created something of beauty from basic raw materials. The farmer who grew the grapes should have this feeling, and the winemakers who grow their own grapes should find it doubly gratifying.

We would like to grow all our own grapes, but these times we find ourselves in, make that impossible. We will have to be content to buy the very best grapes that we can find, and make the best wine we can from them. We attempt to give winemaking the time, attention and love that is needed.

By having our wine sales at the winery almost exclusively, we put ourselves in the position of having our whole operation open to the inspection of our customers. We think that our attitude about the winery is there for everyone to see and feel. We have created a space that we enjoy visiting and working in and we hbpe that everyone who visits it will enjoy it,also.

We like to think that the values by which we live our lives, and by which we make our wines are the same. We strive to do the very best we are capable of, with every facet of our lives, including winemaking.

DEVELOPMENT OF TEST EQUIPMENT CALIBRATION REQUIREMENTS DOCUMENTS

R.A. Schultz
Physicist
Navy Metrology Engineering Center
Pomona, California

INTRODUCTION

The Navy Metrology Engineering Center,Pomona has the responsibility of providing technical guidance and direction to the Navy Metrology and Calibration (METCAL) Program. One of the key elements in this program is the preparation and distribution of Instrument Calibration Procedures (ICP's), including the review of Local Calibration Procedures (LCP's) prepared by various Navy activities and ICP's prepared by contractors prior to distribution. However, differences in the availability of calibration equipment, the calibration method used and interpretation of test requirements have led to considerable variations in calibration documentation. A large expansion of test instrument (TI) inventory, combined with the continual introduction of new calibration equipment including automated calibrators, has made it necessary to prepare many new ICP's and also change, revise and expand existing ICP's. It has become apparent that a new approach to calibration procedure preparation is necessary to cope with the increasing workload and diversity of Navy requirements.

THE PROCEDURE PREPARATION PROBLEM

The increasing procedure preparation workload has escalated the need for uniformity and standardization in calibration procedure preparation. Military Specification MIL-M-38793, Manuals, Technical: Calibration Procedures, Preparation of, provides instructions on the organization, structuring and general contents of a calibration procedure. However, additional information is required to establish a consistent technical approach with respect to the tests performed, calibration test points and ranges selected, and the measurement methods employed. Such guidance is needed to ensure valid calibrations and to achieve maximum efficiency in performing calibrations consistent with prescribed acceptance/ rejection criteria and desired confidence levels for each TI. The current lack of uniformity and consistency in defining test requirements and calibration methodology among various Navy activities and government contractors has limited the serviceability of calibration procedures for Navy-wide use. The above factors have also limited the interchangeability of procedures prepared and used by the three military departments - Air Force, Amy and Navy.

THE CALIBRATION REQUIREMENTS DOCUMENT CONCEPT

I" view of the problems noted above, the Navy's Metrology Engineering Center has initiated development of a series of documents designated as Calibration Requirements Documents (CRD's). These documents establish technical policy for the Navy METCAL Program and provide calibration test requirements for generic families of instruments. The CRD will form the basis for uniform ICP preparation and can also be used far technical guidance in the preparation of LCP's when a" approved ICP is unavailable. Use of CRD's by procedure preparation contractors or government activities will assist in achieving consistency, standardization, and proper technical content in calibration procedures. The CRD can also be used in calibration courses of instruction to explain calibration policy as applied to families or groups of instruments.

INTERSERVICE APPLICATIONS

The Calibration Procedures Working Group, as established under the DOD Joint Technical Coordinating Group, far Metrology and Calibration (JTCG-METCAL), has representatives from the three services with a strong commitment to establish common technical requirements for calibrating selected groups of test equipment. The long range objective of the working group is to promulgate policies and procedures to ensure that the three services develop common, interchangeable calibration procedures. CRD's on Signal Generators, Electronic Counters. Digital Multimeters, RF Wattmeters, coaxial Attenuators, Waveguide Attenuators, Liquid-in-Glass Thermometers, Cable Tensiometers, Pressure Cages, Micrometers and Tachometers have bee" distributed to the services for study. review, changes and final approval.

THE CALIBRATION REQUIREMENTS DOCUMENT IN DETAIL

As presently formulated, the CRD is separated into five sections. Section 1 establishes the basic scope of the document, including a definition of the peculiar category of test equipment addressed; categories excluded from the CRD may also be defined far clarity. Section 2 states the purpose of the CRD, which is to provide technical requirements for achieving and maintaining consistency in the development of calibration procedures and calibration of test equipment. Section 3 refers to applicable reference documents. Section 4 generally consists of a Table and Footnotes, as required. Table 1 describes the basic calibration test requirements including performance parameters to be tested, rationale for conducting tests and choice of test points, and provides guidance for combination and sequence of tests to minimize testing time. The test type is defined by a letter code. Test type A is a parameter/test which verifies specific values/tolerances and which must be performed. Test type B is a test without quantitative tolerances but is critical to the calibration. Test type C is generally tested by inference during successful performance of the prescribed A and B type tests. This section is of major significance in the CRD. Section 5 contains an Appendix with useful information subdivided into four subsections: Subsection 1 lists the applicable reference documents. Subsection 2 provides supplementary information not addressed in Table 1, such as preparations for tests, adjustments, special requirements/conditions imposed on the calibration, and calibration test specifications other than the manufacturer's specifications. Subsection 3 describes functional checks that may be required. Subsection 4 provides a listing of generically-related documentation, such as Measurement System Operation Procedures (MSOP's) and Measurement Method Modules (MMM's). The MSOP describes the operation of a combination of calibration standards or a calibration system in measuring all parameters peculiar to one category of test equipment. The MMM describes the operation of calibration standards or systems for measuring a single parameter which may be applicable to one or more categories of test equipment.

FUTURE DEVELOPMENTS

Although CRD's are required in all the measurement areas, those of greatest importance are categories of test equipment involving newly developing technology or "state of the art" measurements and areas where test requirements are not well defined. These areas include infrared, gas analysis, nondestructive test (NDT), and electro-optical. Priority will also be given to areas subject to widely divergent calibration practices in an effort to achieve early standardization. Examples of the latter are the various types of Automated Test Equipment (ATE) being utilized by the Navy.

SUMMARY

The newly emerging CRD, properly formulated, promises to be an effective coal in standardizing, improving and accelerating calibration procedure development in the Navy and other services. Additional benefits will be a mare efficient utilization of manpower in writing calibration procedures and in performing test equipment calibrations.

Product Assurance of Test Software

by

R. N. Miller, TRW
Redondo Beach. Cal.

As the making of test measurements becomes increasingly automated, it is increasingly important to assure the accuracy and robustness of the computer software which drives the measurement process. Latent faults in software can manifest themselves in several ways, among them being:

- improper display/storage of test data;
- making of inaccurate measurements;
- damage to deliverable end items caused by exposure to inappropriate test conditions
- Computer crash

The effects on test schedules and test validity due to the occurrence of the above or other software induced test anomalies can be significant due to schedule delays resulting from repeated tests or computer downtime. Also the risk inherent in the acceptance of potentially defective equipment which was improperly tested or measured must be considered.

This paper addresses Quality Assurance,Configuration Management, and Reliability Controls found *useful* to reduce the incidence of latent defects in test software. In addition to qualitative procedural controls and test validation of software, some quantitative approaches to estimating the impact of software on test set availability are discussed.

PLANNED SCREENS TO IMPROVE QUALITY AND RELIABILITY

Irving Quart and Albert Samuels: Hughes Aircraft Company

Key Words: Environmental Stress Screening, Product Improvement, Quality Growth, Reliability Growth, Thermal Cycling.

ABSTRACT

To achieve modern field reliability requirements, the quality and reliability effort must go beyond the use of standard quality control techniques, high reliability parts and intensive design analysis. Planning and subsequently implementing effective quality and reliability programs has become crucial. An unfortunate separation of quality and reliability has taken place over the years which no single effort will undo. Recently, however, there has been recognition and some correction of the problem. One such recognition concerns the fact that, although good reliability is conceived in design, it is born alive in manufacturing operations.

Experience has shown that to assure achievement of the reliability goal at minimum cost, it is necessary to include, as part of the growth program, an environmental screening regimen that is monitored and supported by a vigorous corrective action system. This policy is perhaps best exemplified by the Hughes F-15 and F-18 Radar production programs.

This paper will summarize some of the concepts and underlying theory developed at Hughes to facilitate the planning of screening regimens and quality/reliability growth programs. It discusses a production-oriented technique which should aid in the early ferreting out of quality and reliability defects.

HUGHES BACKGROUND

In 1966, Hughes obtained a contract to improve the reliability and maintainability (IRAM) of the MA-l fire control computer. An important element of this project concerned the development of a burn-in regimen for various assembly levels. The effort eventually produced an analytical burn-in model, which formed part of the basis on which Hughes subsequently (in 1970) accepted the reliability requirement for the B-52 FLIR (forward looking infrared) and F-15 radar programs. In the former case it was concluded that with proper in-house screening, the reliability commitment could be met by purchasing MIL-SPEC parts instead of high reliability parts, thus saving the customer at least one million dollars. The B-52 FLIR successfully passed its reliability demonstration test, and field experience exceeded the required reliability. The F-15 Radar has also passed all reliability demonstration tests to date.

RESEARCH AN0 DEVELOPMENT

Since 1973, Hughes has continually funded a research and development program to evaluate the effectiveness of introducing various forms of environmental stress during screening. These investigations include large statistically designed experiments, as well as detailed analyses of the screening data generated by several large production programs.

Screening models currently employed at Hughes were derived analytically and verified by data generated by a number of production programs. The models were further refined by the results of the statistically designed experiments. The initial experiment utilized 954 assemblies and accumulated 6.7 million part-hours (Reference 1). A second experiment included 468 assemblies and 1.1 million part-hours (Reference 2), while a third major experiment involved 800 assemblies and 6.2 million part-hours (Reference 3). The experiments, employing a factorial design, studied the effects of temperature range, rate of change of temperature, and random vibration. Assemblies under test were powered, uncycled and cycled, and unpowered for various time periods. Smaller experiments employing unit level equipment were also performed.

The models resulting from this effort were used to design the screening regimens for the F-18 fire control radar and the A-6 TRAM DRS.

A further development pertinent to the application of the models provides a graphic control chart monitoring technique for the individual screens. Thus, as long as the observed failures versus the number of equipments tested for each screen is in control, the production process is on course and the required reliability will be achieved.

UNDERLYING POSTULATES AND DEFINITIONS

Hughes reliability growth theory is based on the following postulates (Reference 4).

1 Flaws are latent failures arising from imperfections in design, workmanship or material. Flawed items form a separate population possessing a significantly shorter stress life than the typical long life of high reliability items.

2. Even state-of-the-art quality inspection systems involving optical and IR scanners will not uncover all flaws.

3. A failure is the precipitation of a flaw into an observable anomaly of performance. All observable anomalies are not observed; hence, unobserved failures must be taken into account.

4. A screen is the application of **stress** to precipitate failures at a convenient time.

5. The rate at which flaws are forced into failures by a screen is proportional to the number of flaws in the equipment being screened.

6. The number of flaws in a piece of equipment will decrease as more pieces are manufactured and tested, since normal quality control and reliability procedures will correct flaws resulting from assignable causes.

7 Flaws eliminated by the learning process are theoretically nonrecurrent, while flaws removed by the screening process may exist in subsequent equipments.

THE THREE DIMENSIONAL CONCEPT

Product improvement occurs as a result of two simultaneous processes. One process is production learning and is measured by production sequence or time, usually coincident with product serial number. The second process is screening, and is measured by screen time.

The relationship of the two processes is shown in Figure 1. The instantaneous unreliability, that is, the number of flaws of a product, U, represented on the vertical axis, is a function of two independent variables, each representing a different interpretation of time. The effect of learning is represented in the M, **U** plane, and the effect of screening is represented in the t, U plane. Thus, **U(M,t)** depicts the number of flaws of the Mth production equipment at screen time t. The fundamental mathematical model, which combines the learning and screening concepts to produce the three dimensional figure, can be expressed as

$$U(M,t) = U(1,0)M^{-b}(1-b)e^{-\rho t}, \quad M > 10$$

where:

ρ = the environmental severity rate,

U(M,t) = the number of flaws contained in the equipment serial number M at time t,

M = equipment serial number,

b = the constant learning factor.

Each of these factors must be carefully addressed to plan and control a reliability growth program. The following sections further describe the learning and screening processes.

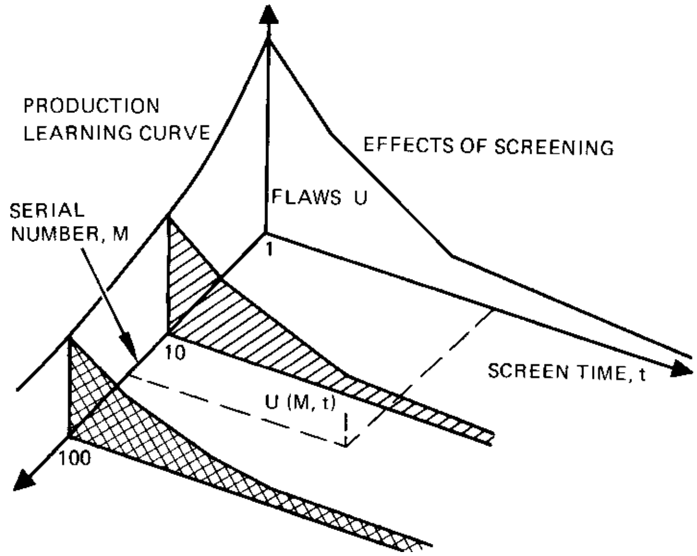


Figure 1. Three Dimensional Concept of Reliability Growth

THE LEARNING PROCESS

For many years the time to manufacture a product was estimated using the classical learning curve model (Reference 5):

$$H_x = ax^{-b} \tag{1}$$

where:

H_x = the cumulative average time to produce the first x equipments,

a = the time to produce the first equipment,

b = the learning curve slope.

Furthermore, the time necessary to produce the xth equipment is defined by

$$h_x = ax^{-b}(1-b), \quad x > 10 \tag{2}$$

On log log graph paper, expressions (1) and (2) can be plotted as the straight lines shown in Figure 2.

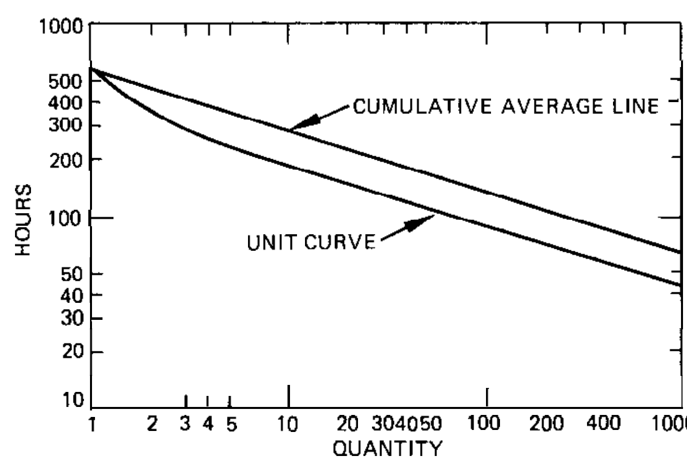


Figure 2. Typical Learning Curve Used in Production Time Estimation

Improvements in workmanship and processes and the implementation of design changes to correct problems are among the reasons for the reduction in time to produce successive equipments. Since these activities also remove flaws in the equipment, expression (1) can be rewritten in terms of flaws to conform to the time designations previously discussed. Thus,

$$U(M,0) = U(1,0)M^{-b} \qquad (3)$$

where:

$U(M,0)$ = the cumulative average number of flaws for equipments 1 through M at screen time of 0,

$U(1,0)$ = the initial number of flaws in the first equipment,

b = the learning curve slope.

Furthermore, the number of flaws of an individual equipment at any screen time, t, can be written as

$$U(M,t) = U(1,t)M^{-b}(1-b), \quad M > 10 \qquad (4)$$

The latter relationship was successfully verified by three Hughes production programs, each of which produced approximately 250 systems (shown in Figures 3a, b, and c). The classical learning process relationship expressed in terms of time to produce the xth equipment given by expression (2) properly holds when expressed in terms of the number of flaws of the Mth equipment at stress screen time, t, as given by expression (4). The effect of the stress screen time on the number of flaws will be derived in the following section.

THE SCREENING *PROCESS*

Three different screening models employed by Hughes are LOOK AHEAD, CREDIT and AFAR. The three models evolved from the same basic approach and differ only in the Level of detail that may be attained and the method of calculating the strength of a screen.

The models are based on the postulate that for each and every serial number, the rate at which flaws are forced into failures by a screen is proportional to the number of flaws in the equipment being screened; i.e..

$$\frac{\Delta U}{\Delta t} \propto U$$

where:

U = number of flaws in an equipment

ΔU = the incremental **change** in U, and

Δt = the incremental time the equipment is exposed to an environment.

Thus,

$$\frac{dU}{dt} = -\rho U$$

and by integration,

$$[\log U]_0^t = [-\rho t]_0^t$$

$$U_t = U_0 e^{-\rho t} \qquad (5)$$

By definition, ρ is the environmental severity rate (ESR). U_t represents the number of flaws in the equipment at the end of screen time t and U_0 represents the number of flaws in the equipment before the application of the screen.

It follows from expression (5) that the number of flaws in the first equipment at time t can be determined by

$$U(1,t) = U(1,0)e^{-\rho t}$$

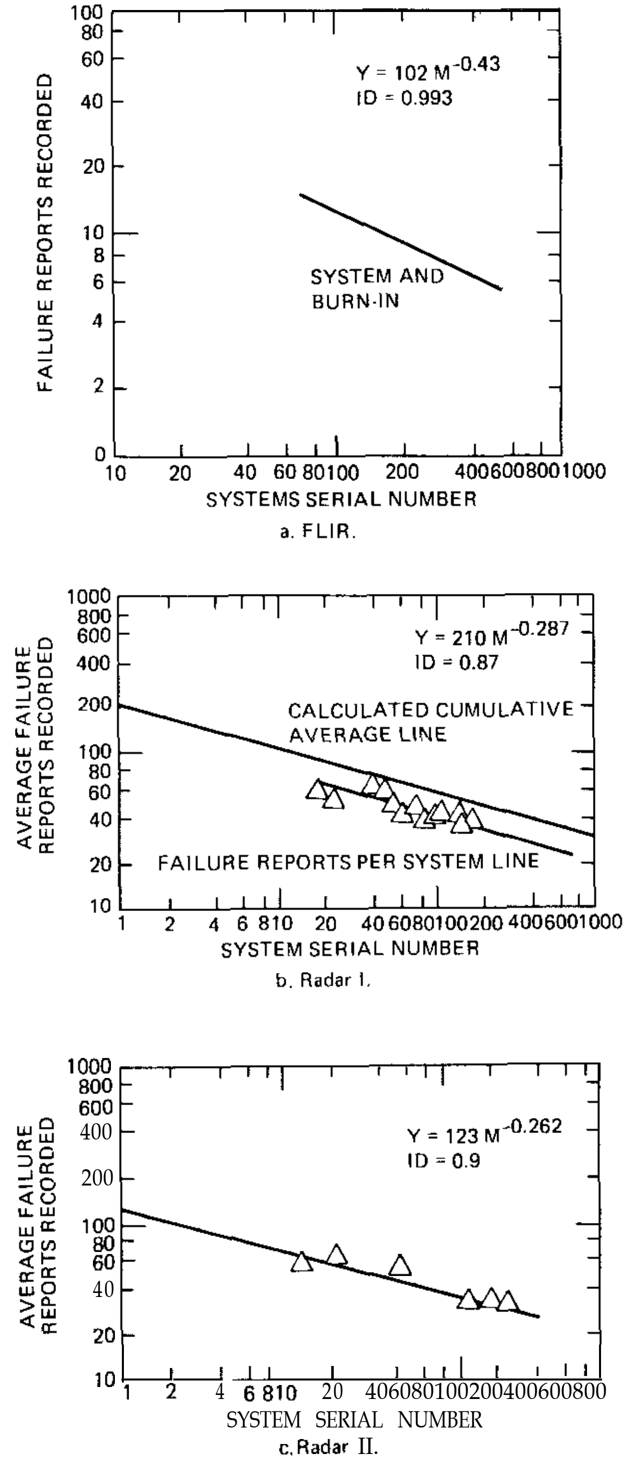


Figure 3. Cumulative Average Failure Reports per System versus System Serial Number

and appropriate substitution of the above into the learning process relationship given by expression (4) yields the fundamental AFAR growth model

$$U(M,t) = U(1,0)M^{-b}e^{-\rho t}(1-b), \quad M > 10 \qquad (6)$$

An expression analytically usable for all serial numbers is:

$$U(M,t) = U(1,0)[M^{1-b} - (M-1)^{1-b}]e^{-\rho t}$$

The asymptotic form shown in expression (6) is sufficiently accurate for regions of practical interest.

The fundamental quantitative result of a screen or a test is the number of failures observed. In this case, the expected number of failures, f, that will be observed upon applying a particular screen is calculated by

$$f = D\, U_o(1 - e^{-\rho t}) \quad (7)$$

where D represents the detection efficiency. This result can be justified by recognizing that the number of observable failures for a particular screen is $U_o - U$, and the expected number of observed failures depends on the ability to detect the observable failures, thus

$$f = D\,(U_o - U_t) \quad (8)$$

Substituting expression (5) for U_t in expression (8) yields expression (6).

DETECTION EFFICIENCY

The number of failures detected by a particular screen is influenced by the diligence and precision with which anomalies are sought. This factor is taken into account by the growth model in the form of the detection efficiency parameter, D.

Historically, detection efficiency is not routinely measured. Often, narrow interpretation or bias to prevent self-incrimination can lead to inflated estimates of achieved detection efficiency. Also, since D is the product of many probabilities, it is easy to understand why detection efficiency can be low.

Other factors that affect detection efficiency include the change in test tolerance as equipment becomes more complex, the design schemes employed to make the equipment less sensitive to major changes in part values, and the number of built-in tests conducted.

THE ESR

The environmental severity rate (ESR or ρ) is dependent on the equipment and the environments imposed on the equipment by the screen. Since ESR is a rate, it must be expressed per some unit of time. Since the number of cycle repetitions is a paramount factor in screening effectiveness, the duration of one complete cycle, t_c, becomes a convenient unit of time.

As a first approximation, it is assumed that the numerator is the product of two independent factors. One, f(E), is a measure of susceptibility as a function of equipment type; the other, h(S), is the effect of environmental stresses.

Thus,

$$\rho = \frac{f(E)\ h(S)}{t_c}$$

It turns out that f(E) is well-fitted by a ratio of part types, called E for convenience. However, h(S) is a complex function of the strength and type of applied environmental stresses.

K. L. Wong s paper (Reference 6) covers failure rate models for five stresses. These stresses are shown in Table 1. The current and voltage stresses will be combined into a single multiplier in this paper. In two experiments performed at Hughes (Reference 7), the power On results were compared to power Off. The application of power was found to double the failure rates. The temperature model follows the form used in MIL-HDBK-217C (Page 2.1.5.3), but with a slight modification regarding the lower than 25°C region. Since most electronic parts are manufactured at room temperature, equal temperature deviations from either side of 25°C should cause the same increase in failure rate. For example, -50°C should be as effective as 100°C.

Thus, a generalized model for ρ assuming no other interactive terms and no other stresses is:

$$\rho = \frac{E}{t_c}\left[\rho_T + \text{Pi} + \rho_V\right]$$

$\dot{T}$ is shorthand for rate of change of temperature, $\frac{dT}{dt}$

where:

$$\rho_T = S_T \sum_{i=1}^{n} P_i t_i e^{-K_1 \pi_i}$$

TABLE 1. SUMMARY OF STRESSES AND RELATED FAILURE RATE EXPRESSIONS FOR SELECTED PROCESSES

stresses	Failure Rate* Expressions	Remarks
Temperature, T	$e^{-K_1/T}$ (For most of the processes)	T in °K
Number of Thermal Cycles, N	$\frac{N}{t}(\Delta T) K_2, \frac{N}{t} e^{-K_3/T}$ (Effects of low cycle fatigue)	t = time T = cycling temperature range
Voltage, V	TV (Effects of insulation breakdown)	
Current, I	$\frac{I^n}{T} e^{-K_4/T}$ (Effects of electromigrations)	n varies from 1 to 3
Vibration	$v^{(1\ K_5)} e - K_6/T,\ g^{K_7}$ (Effects of both low and high cycle fatigue)	v = frequency g = acceleration in number of gs K, = varies with equipment (a value of roughly 4 for some air-to-air missiles tested)

*All Ks are positive numbers and are equipment dependent constants.

$$\rho_{\dot{T}} = S_{\dot{T}} \sum_{m=1}^{n} P_m \frac{dT_m}{dt}^{K_2} t_m$$

$$\rho_V = S_V \sum_{1=1}^{n} P_1 t_1 g_1^{K_7} e^{-K_8 \pi_1}$$

t_c = time to complete one cycle

$$\pi = \left(\frac{1}{298 + IT - 251} - \frac{1}{298}\right)$$ which is the normalized temperature **coefficient**

T = average part temperature (C)

P = 1 or 0.5 depending if power is On or Off

S_T = temperature susceptibility rate

$S_{\dot{T}}$ = rate of change of temperature susceptibility rate

S_V = vibration susceptibility rate

and K,, K_2, K_7 and K_8 are positive number constants.

Note that the environmental portion of ρ, h(S), also contains susceptibilities. These are specific susceptibilities, i.e., linear fitting coefficients for each of the specific types of environments applied. In reality a matrix of susceptibilities, S_{ij}, probably exists, relating each environmental type with each equipment type. Yet the above simplification into the product of two independent factors, one relating to equipment type, the other to applied stresses, gives excellent results.

The model for ρ can be further simplified by the following assumptions:

1. K_1 and K_8 are equal. The value used will be 2298, which has been used on at least two successful screening programs. This represents the normalized failure activation energy.
2. K_2 and K_7 are assumed to be equal to unity for the equipments considered. If K_2 = 1 then t dT/dt = AT, range of temperature excursions.

3 The equipment susceptibility (E) is equal to the total number of parts divided by the number of ICs and hybrids:

$$E = \frac{\text{Number of Parts}}{\text{ICs + Hybrids}}$$

The E factor indirectly reflects many things, including vintage of design, mix of parts and whether the equipment is analog or digital.

Thus, for a given equipment and screening profile, the model has only three unknowns, i.e., S_T, $S_{\dot{T}}$ and S_V. These unknowns need to be determined from the effects of screening on the equipments of interest.

SOLVING FOR S_T, $S_{\dot{T}}$ AND S_V

These three unknowns were solved using data from a FLIR system and two radars. Bear in mind that the values obtained for these unknowns may be applicable to these systems only. The characteristics of the systems with respect to part-count complexity are shown in Table 2. The unit-level screening data for the FLIR and Radar I were used for this analysis, and were combined and treated as one set of data. The system screening data were used for Radar II because not all of the Radar II units were screened at the unit level. The ESR model was developed to use actual part temperatures and not the chamber temperatures that are usually specified.

TABLE 2. SYSTEM CHARACTERISTICS

Program Designation	Approximate Parts Count	IC + Hybrid Count	Number of Systems Included in Data
FLIR	8,100	374	100
Radar I	27,703	2,956	50
Radar II	17,578	5,937	74

The ESR for each equipment was determined using failure and screening time data from many systems. The best fit

two:l on the equipment from which the

S_T,e p$S_{\dot{T}}$inent data required to calcul S_V

FLIR:10^{-4} = $\frac{21.7}{9}$ S_T + $S_{\dot{T}}$ +3.1 S_V)

RADAR I: 178 X 10^{-4} $\frac{9.4}{8}$ (1 6S_T9 $S_{\dot{T}}$ +5.4S_V)

RADAR II: 106 X $\frac{2.9}{3.25}$) -(5 .S_T5 $S_{\dot{T}}$ + 2S_V)1

The above set of equations can be used to calculate the following:

S_T = 3 . 3$10^{-4}$

$S_{\dot{T}}$ = 0.55 x 10^{-4}

S_V = 3 . 3$10^{-4}$

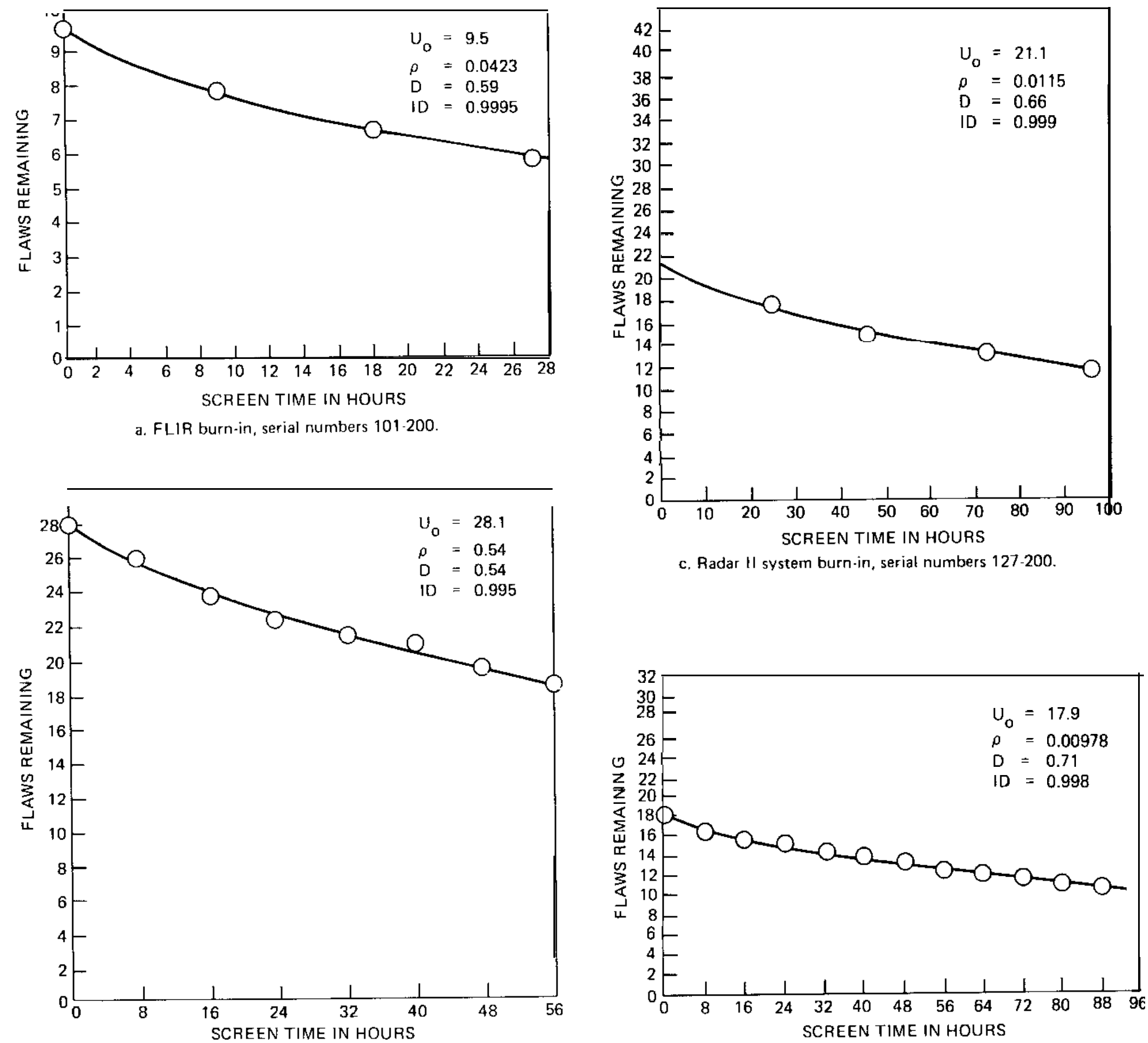
$$\rho = \frac{E}{t_C}\left[3.3 \times 10^{-4} \sum_{i=1} P_i t_i e^{-2298}\left(\frac{1}{298 + |T_i - 25|} - \frac{1}{298}\right)\right.$$

$$10^{-4} \sum_{m=1} P_m \Delta T_m$$

$$\left. + 3.3 \times 10^{-4} \sum_{1=1} P_1 t_1 g_1 e^{-2298}\left(\frac{1}{298 + |T_1 - 25|} - \frac{1}{298}\right)\right] \quad (9)$$

"ΔT_m". Note that

K_2 temperature change for



a. FLIR burn-in, serial numbers 101-200.

b. Radar I burn-in, serial numbers 101-150.

c. Radar II system burn-in, serial numbers 127-200.

d. Radar II system burn-in, serial numbers 151-350.

Figure 4. Flaws Remaining Versus Screen Time

MODEL USE

One of the uses of the model is to evaluate changes to ongoing

TABLE 3. CHANGE IN ρ WITH CHANGE OF SCREEN

	FLIR		
	−8%		
$\dot{T}$	+17%	+11%	+30%
	+6%	+10%	+4%
temp	+6%	+11%	+1%

more the time in other

a

The assumed test conditions to which Radar I is to be subjected are listed in Table 4.

TABLE 4. RELIABILITY DEMONSTRATION TEST CONDITIONS

Temp range	−54 to 71°C
Dwell at high temp	2 hours after stabilization
Temperature rate of change	5°C/min
Vibration	10 min/hour 2.2 ± 0.2 g, sine at a single non-resonant frequency
Fixed time	100 hours on
Nominal cooling	Same as during screening

The ESR is calculated by adjusting the original calculations using the data in Table 4. The number of flaws at the start of the reliability test is equal to the number of flaws at the end of the Radar I screen (Figure 3b). Although the screen detection efficiency D is about 0.55, it is assumed that a more comprehensive test will be used for the reliability test. A compromise D value of 0.8 is used for the reliability test.

The results of the calculations of expected number of failures (F) are shown in Table 5. The probability of passing the reliability test can be determined from the table. The costs of **changes to** achieve the desired risks of failure can be evaluated. Management can now trade off costs versus risks and make more meaningful decisions.

TABLE 5. RELIABILITY DEMONSTRATION FAILURES-RADAR I

Condition	ρ	U_0/Sys	t	D	F
Two systems	0.0223	18	90	0.8	25
One system	0.0223	18	181	0.8	14.2
Increase dwell time to 10 hours	0.0158	18	126	0.8	12.4
Improve screen	0.0223	9	181	0.8	7.1

From Table 5, one can see that:

1. Using one system results in less failures than two systems, thus improving the chances of passing the reliability test.
2. Extending the dwell time with equipment ON, decreases the number of chamber hours as well as the expected number of failures.

ECONOMICS

The payoff in these procedures is an important consideration. Based on the experiments conducted at Hughes and reported in the 1980 R&M Symposium, [Reference 7], properly designed screens can be economical. Simple unpowered temperature cycling can reduce failures in the next higher level of assembly by as much as fifty percent. One of our high reliability radars, which is meeting its reliability requirement in the field, has three levels of screening. As complexity level increases, the number of total failures per system decreases. How much screening at which level is most economical depends on each organization and only the user can design an economical screening regimen for use in his factory.

CONCLUSION

Using the concepts presented here and the failure data developed by user organizations, it is possible to design and monitor a screening regimen that will be economical for the producing organization and will deliver high reliability equipment to the user.

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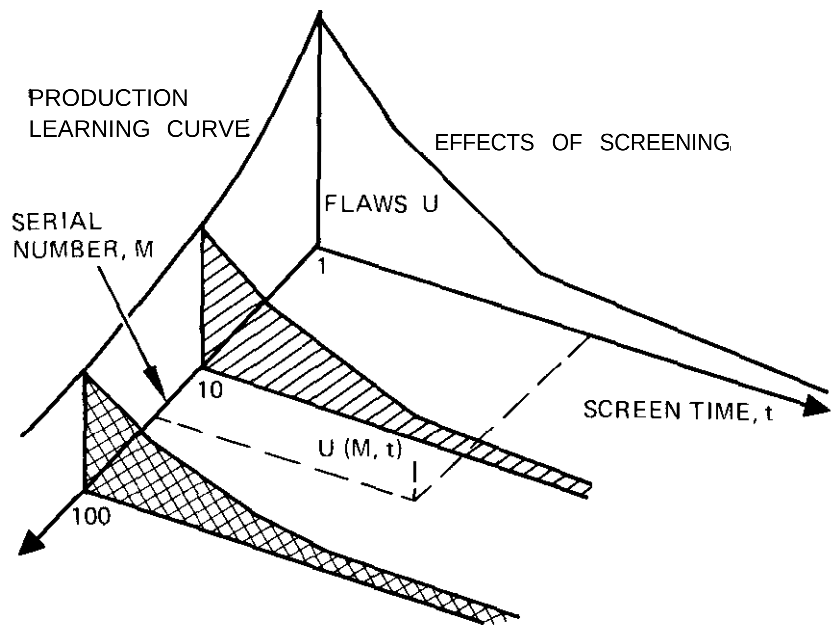
BIOGRAPHIES

Irving Quart has more than 35 years experience in Quality Control and Reliability. The last 20 years have been spent at Hughes Aircraft Company where he is a Senior Scientist in the Reliability Department. For the last 7 years, Mr. Quart has concentrated on the study of reliability growth and environmental stress screening. He has a BEE degree from Cooper Union and a MSSM from USC, and is a registered Professional Electrical Engineer in the State of California. He is a senior member of IES, and a member of IEEE and is listed in Who s Who in the West.

Albert Samuels has nearly 30 years experience in systems analysis and reliability. The last 10 years and 3 prior years have been spent at Hughes Aircraft Company where he is a Senior Staff Engineer in the Reliability Department. Mr. Samuels is in charge of Advanced Reliability Program activities, and is extending reliability growth and screening theories to cryogenic coolers and VLSI/VHSIC chips. He has a BS in physics from the University of Arizona, and is a registered Professional Engineer (Quality Engineering) in the State of California. He is a member of the IEE, IES and the RESA Society.


PRODUCTION
LEARNING CURVE
EFFECTS OF SCREENING
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SERIAL
NUMBER, M
1
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100
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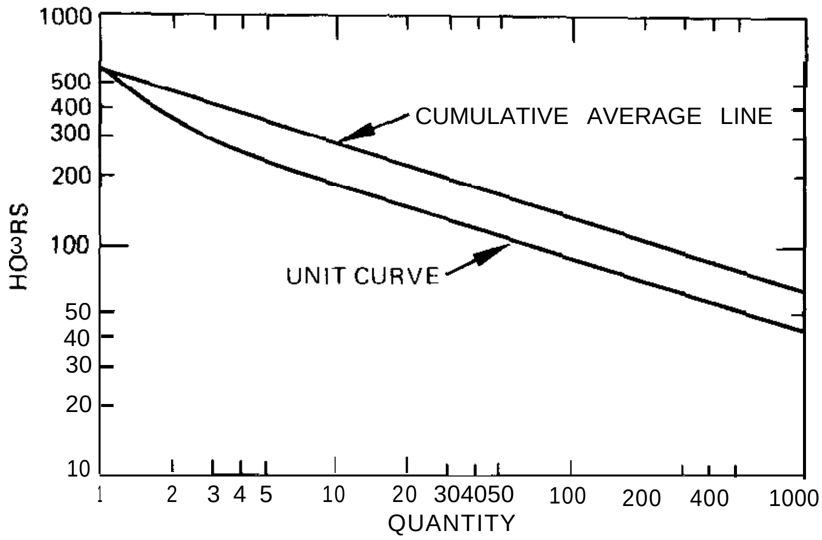
U (M, t)


1000
500
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10
HOURS
CUMULATIVE AVERAGE LINE
UNIT CURVE
1
2
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4
5
10
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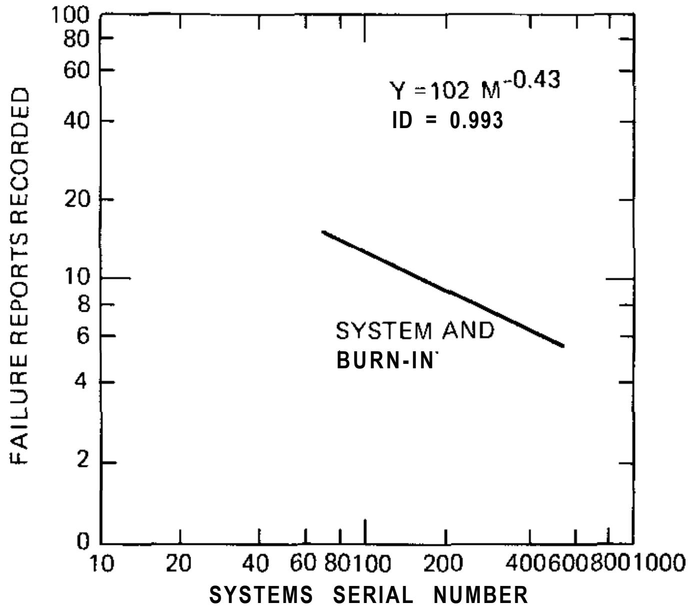
30
40
50
100
200
400
1000
QUANTITY



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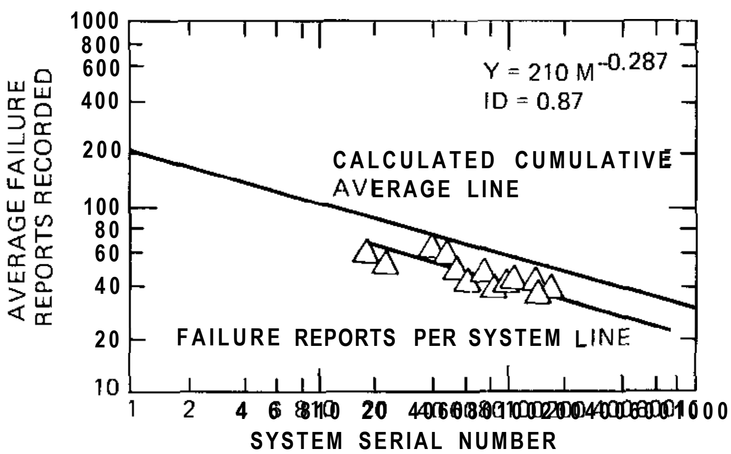
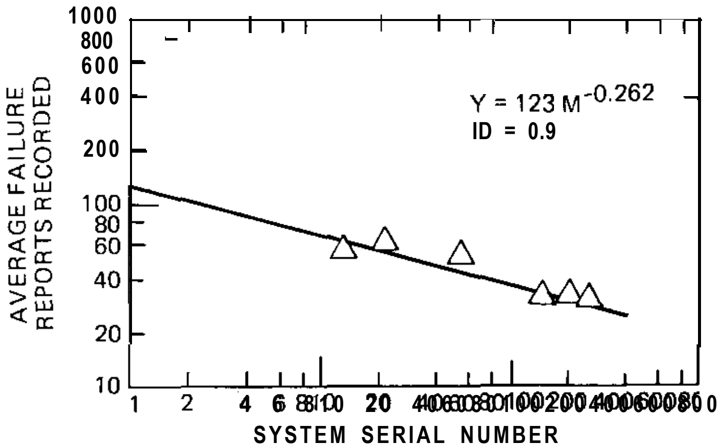
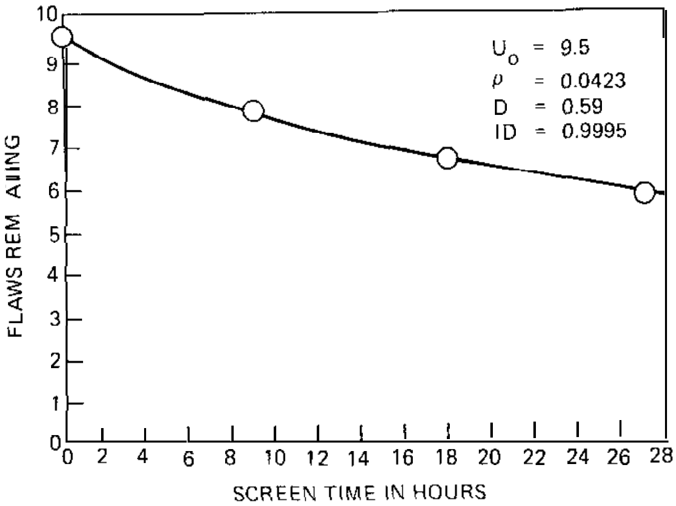


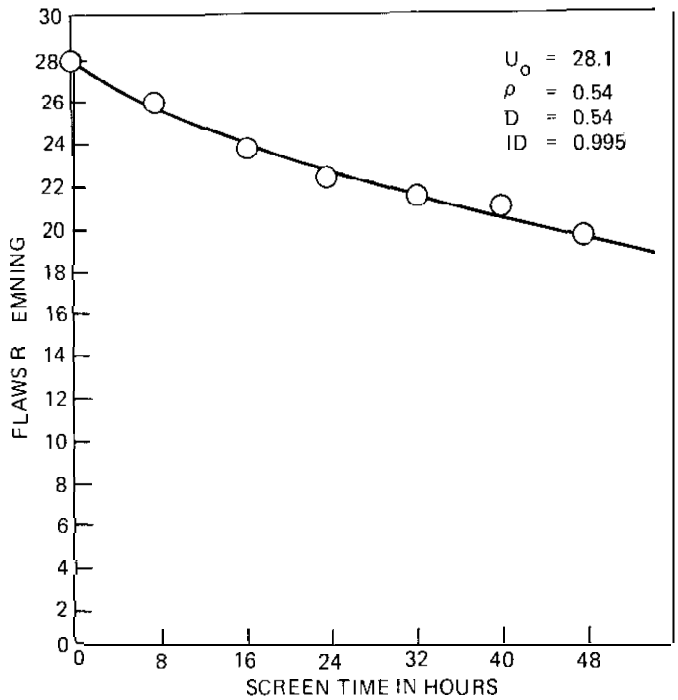
b. Radar I.



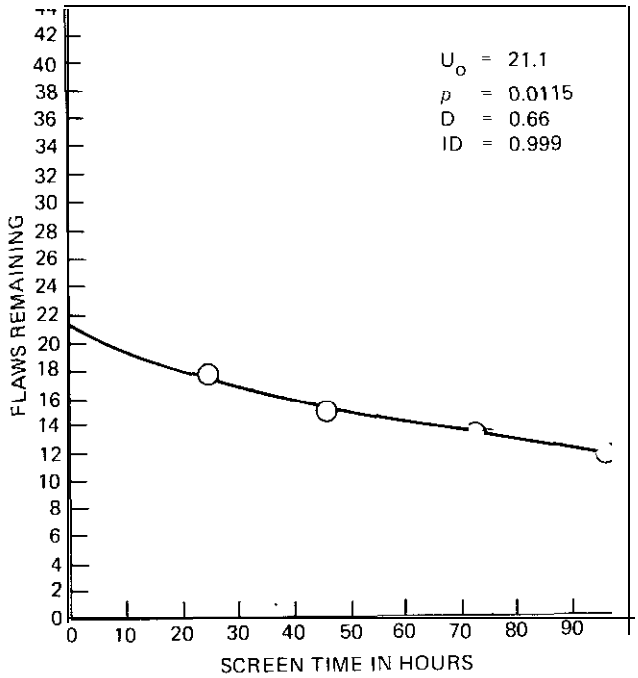
c. Radar II.



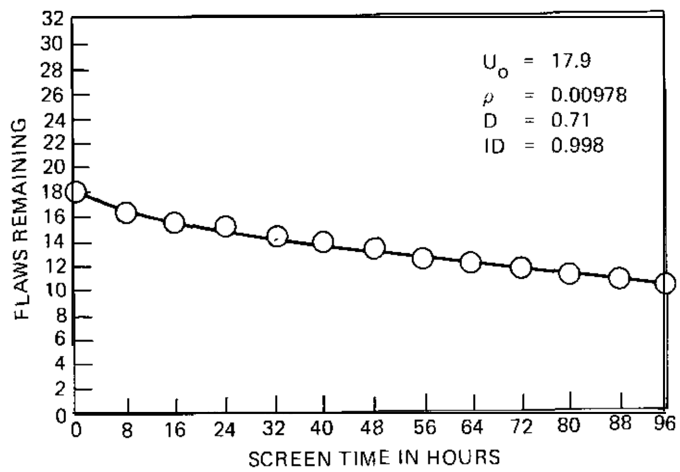
a. FLIR burn-in, serial numbers 101-200.



b. Radar I burn-in, serial numbers 101-150



c. Radar II system burn-in, serial numbers 127-200.



d. Radar II system burn-in, serial numbers 151-350.

THE APPLICATION OF QUALITY ASSURANCE PROGRAMS TO SERYICE INDUSTRIES

Fred H. Sieg
SIMCO
382 Martin Avenue
Santa Clara, CA 95050

ABSTRACT

The concept that the quality of product can be better assured through a formal program of planning and control is just as valid for organizations that provide services as it is for manufacturing organizations. An increasing number and variety of service organizations are recognizing this fact and are finding that accepted quality assurance principles can be effectively applied to their special needs.

This paper reviews and discusses the structure of a quality assurance program, the benefits of such a program and finally presents each of the quality assurance elements that must be considered in the development of a program.

INTRODUCTION

Efforts by producers to assure that their products or services satisfy customer's expectations have gone through many stages as production has evolved from low volume, labor-intensive craftsmanship to the high volume, high technology businesses of today. As our organizations become larger, our products more complex, our workers more mobile, and constraints more binding, product quality becomes increasingly dependent on good planning and organizational efficiency. The realization is being forced upon us that a changing environment demands changing philosophies and practices, and that the rewards go to those flexible enough to take adequate and timely action. The ultimate goal of quality assurance is to keep the customer's experience with the product satisfying and the producer's efforts profitable in the face of these changes.

Taking Quality Assurance in the larger context it is not necessary for the product to be hardware in order for quality assurance practices to apply. The quality and reliability of services is just as responsive to a sincere commitment to quality as are manufactured items. Quality Assurance programs are being adopted in many businesses today to provide the systems that will result in consistent customer satisfaction. These businessess are attempting to assure product quality throughout the process, thereby avoiding the vicious firefighting cycle of letting problems happen then rushing around to correct them after the fact. The applications of quality assurance to non-manufacturing businesses ranges from R&D projects[1], to banking[2], to hospitals[3], to the fishing industry[4], just to mention a few. It is interesting to note that in general these applications of quality assurance are along the lines defined by programs developed for manufacturing. In other words, quality problems seem to be rooted in the basic systems and practices of organization with the substandard product, whatever it is, being the symptom rather than the disease. Quality programs try to cure the disease.

STRUCTURE AND DEYELOPMENT

Developing a quality program begins with considering all aspects of an operation that can contribute to customer satisfaction. Having identified these activities, each is defined in terms of what must be done, who does it, and how it must be done. The interrelationship of the various organizational units must receive careful consideration for it is at these boundaries that most quality problems originate. If carried out objectively this planning process will expose shortcomings in policies and practices which, if corrected, will prevent many problems downstream. The final step in this phase of the program development is documentation in the form of a program manual. This manual outlines the various quality-related activities and identifies the what, who, and how for each. Essential to eventual implementation of the program will be training, instruction, and more detailed procedures in some of the areas.

The development and implementation of a quality program in an established organization can be traumatic to say the least, and its most vigorous opponents are the staunch defenders of the walls of functional empires. This is the most critical point since a smooth-flowing process increases the assurance that the job will be done right and functional discords are the rocks and rapids in the flowwhich cansink the program as soon as it is launched. Experience with the zero defects programs that were popular several years ago taught us that the worker had no control over at least 80% of the quality problems generated. The responsibility for the bulk of the problems fell directly on management in the form of inadequate training and direction at all levels, poor product design, inadequate facilities, and incorrectly specified or substandard materials. The point is that there must be a clear mandate from management that quality and productivity are basic objectives of the company and that obstacles to achieving them will not be tolerated[5]. Without this and without top management's active participation, attempts to implement a quality program will be an exercise in futility. A management outline of quality program development could include these five action areas:

Make quality leadership a basic strategic goal

Translate company quality strategy into clear customer-oriented product specifications

Quality action throughout entire company

Clarify the work of the quality function itself

Continuous motivation, commitment, and measurement throughout the company

Fortunately, the growing quality consciousness in our society is helping to open top management doors that have traditionally been closed to the total quality concept. This has resulted in a rapidly increasing number of U.S. companies launching effective quality programs.[5]

BENEFITS

So far this has been a general discussion of what a quality program is and some of the obstacles to establishing one. At this point we should consider some of the specific results of an effective program. Stated concisely, the purpose of a quality program is toassurethat you "do it right the first time." Using customer satisfaction as the company's prime objective, this means that every activity related to that end from the time that an order is accepted to the time that the product is in the customer's hands must be done right the first time. It sounds like a big job and it is, but so is constantly correcting mistakes, explaining late deliveries and processing warranty claims and customer complaints.

Customers frequently judge vendor performance on cost, delivery, and quality. To these I would add suitability: was the customer's need interpreted correctly? Each of the above areas benefits from an active quality program.

The inadequacy of marketing and internal specifications to clearly define the customer's quality use requirements is one of the weakest links in the chain of quality-related activity.[6] The program must address the methods of accurate interpretation and transmission of the customer's need to each area involved in the conversion of that need to the finished product.

The immediate cost of poor quality in terms of rework, scrap, excessive inspection and warranty service can run as high as 15% of sales. These costs normally find their way into overhead and become part of the price of the product. The initial impact of an effective quality program in an organization with serious quality problems can be a three-to-one payback. Three dollars returned for each dollar spent on quality improvement. Obviously these savings if reflected in product price can result in more competitive pricing.

The reasons given for missing promised delivery dates are legion. Several of the more common causes that are addressed by a quality program are:

1. Critical vendor parts and materials are late or are substandard when received.
2. Necessary equipment or work instructions are not available to do the job.
3. Errors in the product are detected and have to be corrected before delivery.
4. Absence of key personnel without trained back-up for the job.

Control of the above items can not only reduce late deliveries but also result in shorter lead times across the board.

Quality as a factor in judging vendor performance is measured in terms of the percentage of a vendor's shipments that can be accepted and used without problems. If the vendor's product from delivery to delivery is correct, complete and consistent, the quality rating will be high. In the type of business most of us are in, paperwork and records are an integral but often misunderstood part of the services we perform. The 3 C's mentioned above apply equally to the service and the paperwork.

Most businesses know how to produce to a given quality level and they do it some of the time. The problem in many cases is that an informal or unplanned approach is used which does not result in a smooth-flowing system of activities even though each person may be an expert on his own job. What the customer sees is inconsistency, incorrectness, and incompleteness of product or service. A system and the organizational discipline necessary to direct all individual activities toward a common end are lacking. The quality program defines the network of administrative and technical procedures required in an organization to produce and deliver a product of specified quality standards. The elements of such systems have been documented for many years. Unfortunately, the concept of total quality control (assurance) emerged from the quality profession in the 50's and its first major application was a government standard. Traditionally, both quality control and government standards have been regarded at best as necessary evils and are given little if any credence. It is thought-provoking to wonder if we would be facing today's serious problems of quality and productivity if the total quality concept had been introduced and promoted by Harvard Business School savants as a new and effective management philosophy.

ELEMENTS OF A QUALITY PROGRAM

Back to the subject, in 1961 A.V. Fiegenbaum, a quality control manager with General Electric, published the book "Total Quality Control" which emphasized the systems approach to product quality.[7] His studies showed that as many as 300 elements could be encompassed in a quality system. These he reduced to the following 10 general categories:

1. Pre-production evaluation
2. Product and process planning
3. Purchased material planning, evaluation, control
4. Product and process evaluation and control
5. Quality information feed-back
6. Quality information equipment
7. Quality training, orientation, and manpower development
8. Post-production service
9. Management of the Q.C. function
10. Special quality studies

The concept created great interest in quality circles but no sweeping changes in management philosophy of quality control. In 1959 MIL Q 9858, "Quality Program Requirements" was issued and in 1963 superceded by MIL Q 9858A which is in use today.[8] This specification covered essentially the same elements as those analyzed in Fiegenbaum's book. Originally, MIL Q 9858A was a contract requirement for high reliability items and most companies that tried to fit it to an inspection-oriented system experienced great difficulty in adjusting to the prevention/assurance concept of the document. Acceptance of the concept by commercial companies was a slow process and tended to be regarded as "too expensive," "too restrictive," "too idealistic," ad infinitum. However, the influence exerted by MIL-Q-9858, the quality programs developed by some of the technical giants like IBM and Xerox, and by professional societies such as ASQC kept the concept alive. Finally, to all appearances, today total quality assurance is an idea whose time has come.

APPLICATION

In developing a quality program to fit a specific business it is better to start with a larger number of elements and then condense and modify as the situation demands. The ANSI/ASME NQA-1 lists 18 basic requirements that can serve as a manageable development outline.[9] They are:

Organization

The structure, functional responsibility, level of authority, and lines of communication for all activities affecting quality must be documented. Responsibility for the establishment of a Quality Assurance program and its implementation shall be assigned. Persons or organizations assigned this responsibility must report to a management level such that required authority and organizational freedom are provided, including sufficient independence from cost and schedule considerations to make objective decisions.

Quality Assurance Program

Provision must be made for a documented quality assurance program to be planned, implemented and maintained. The program must consider the adequacy of equipment, environment, and assurance activities employed in meeting the prerequisites for quality-related activities. The program must also provide for the necessary training of-personnel performing activities affecting quality. Regular assessment of the program to assure its effectiveness shall be made by the management responsible for each part of the program.

Design Control

The design must be defined, controlled, and verified. Design interfaces shall be identified and controlled. Verification of design adequacy must be made by persons other than the designer. In a service organization this section will relate to the procedures and documents used to assure that the customer's need is clearly identified and translated into whatever type of work order/job instruction used in that particular organization.

Procurement Document Control

Procurement documents shall require as necessary the supplier to have a quality assurance program. These documents must reference applicable standards and requirement. Provisions must be made for review of procurement documents, usually by quality control, to assure that the items or services will meet the specified requirements.

Control of Purchased Items and Services

The procurement of items shall be controlled to assure conformance to requirements - procedural as well as material. These controls include: (a) vendor selection and approval, (b) control of procurement documents, (c) acceptance procedures, such as receiving inspections (d) procedures for handling non-conforming purchased parts and for obtaining correction, (e) maintenance of quality assurance records related to purchased items and services as well as vendor evaluation.

Instruction, Procedures, and Drawings

Activities affecting quality must be prescribed by documented instructions, procedures, or drawings. This documentation should contain acceptance criteria for determining that the prescribed activites have been performed satisfactorily.

Document Control

The preparation, issue, and change of documents specifying quality requirements or prescribing activities affecting quality must be controlled. The control is to assure such documents have been reviewed and approved and that the correct documents are being employed.

Identification and Control of Items

Items or services shall be identified from initiation of the process up to and including delivery to the customer. The identification must relate the item or job to an applicable 'specifying document. Identification must extend to items or materials in stock.

Control of Process

Processes affecting quality of items or services must be controlled. Control is by instructions, procedures, checklists, travelers *or* other means. These controls must include process parametersand environmental conditions when required. It should be noted that 'process' here refers to support systems such as order processing and specification documentation as well as the actual production activity. I have seen many companies with excellent controls in the processing area plagued with quality problems generated in the "front office" paperwork.

Inspection

Verification of conformance of an item or activity to the specified requirement by persons other than those who performed the work is required. The inspection activity must be planned and documented.

Test Control

Tests required to verify conformance to specified requirements. These tests must be planned, documented, and conducted by qualified personnel.

Control of Measuring and Test Equipment

This control system must address the selection of adequate equipment, its calibration and control, its handling and storage and the documentation and maintenance of records related to the system.

Handling, Storage and Shipment

Handling, storage, cleaning, packaging, shipping and preservation of items shall be controlled to prevent damage or loss.

Inspection, Test, and Operating Status

The status of inspection and test activities shall be identified through indicators such as physical location, tags, markings, shop travelers, stamps or other suitable means.

Control of Non-Conforming Items

Items that do not conform to specified requirements must be controlled to prevent inadvertent use. Controls must include identification, documentation , segregation, and evaluation.

Corrective Action

Conditions adverse to quality shall be identified promptly and corrected as soon as practical. Procedures for the identification, cause, corrective action, documentation and follow-up must be established.

Qualitv Assurance Records

Records that furnish documentary evidence of quality shall be specified, prepared and maintained. Responsibility for record maintenance should be specified.

Audits

Planned and scheduled audits must be performed to verify compliance with all aspects of the quality program and to determine its effectiveness. Audits must be performed to documented procedure and the results documented and reported to responsible management.

The development of a program that will meet the specific requirements of a business is best performed by someone with experience at least in working with quality programs. Ideally the development of a program should be done by someone outside the organization who will be less influenced by the politics and ingrained practices that are present in every group. The plan must be tailor-made to the producer's organization, market, and capability. Thorough analysis of these items are absolutely necessary to the synthesis of an effective plan.

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THE CHALLENGE OF SEMICONDUCTOR METROLOGY

Judson C. French
Kenneth F. Galloway
Robert I. Scace
Center for Electronics and Electrical Engineering
National Bureau of Standards
Washington, D. C. 20234

ABSTRACT

Semiconductor technology has placed challenging demands on the metrologist to provide state-of-the-art capabilities for measurements of dimensional, electrical, thermal, and other physical properties of semiconductor materials. devices, and circuits in a form suitable for meeting the practical needs of science and of industry and its customers. The National Bureau, of Standards is responding to these demands by providing generic new measurement methods, physical standards, and services, highlighted by examples given in this paper.

1. INTRODUCTION

In broad areas of scientific, industrial, and governmental measurement activities, the traditional metrological services, such as hierarchical calibration laboratory systems, that have assured adequacy of precision and accuracy in practical measurements in the past continue to be an essential element of metrology, but they are no longer sufficient in themselves.

There are several reasons for this change.

Practical measurements now require unprecedented sensitivity, precision, and accuracy, over an extremely wide range of material or system properties and signal characteristics. This is true in the research laboratory, on the production line, in the field operations of the military services, and in measurements in support of governmental regulatory efforts concerned, for example, with air or water pollution and electromagnetic radiation intensity.

The requirements of these practical measurements may be close to or exceed the state of the measurement art, and yet reproducibility of the measurements between various concerned parties, and accuracy based on accepted national or international standards, are important for the legal requirements of regulatory agencies, for equity in the marketplace, for reliability of the performance of critical products or systems, and for enhanced productivity in the manufacturing and process industries.

In many cases, these measurements must be made at very high speed, either because of the transient nature of the signal itself or because of the necessity for making a large number of repetitive measurements in reasonable times. Often it is impractical for measurements to be made effectively by hand; automation of the process becomes essential where the required speed and quantity of measurements exceed human capabilities, or where the measurement must be performed in places unsafe for, or inaccessible to, a human operator.

In particular, the pervasive application of electrical and electronic systems for control and communication and for energy generation and transmission has both broadened the availability of new measurement methods and extended to new extremes the range of electrical signals and properties to be measured and controlled. The burgeoning field of solid-state electron devices has produced new tools such as the microprocessor to aid in automation of measurement. It has simultaneously placed new demands on the measurement art for sensitivity and speed in measurements through its routine needs for part-per-billion sensitivity in measurements of the properties of solid-state materials used in the manufacture of these devices, and for speed in measurement of the properties of devices intended for use in information systems operating in the gigabit-per-second range.

Thus, to respond to these new levels of sophistication and complexity, new services are needed from our national measurement laboratories and throughout the measurement chain extending from national laboratories to the place where practical measurements are carried out. These new services may take the form of improved measurement assurance programs, new physical standards, or prototype instrumentation or design data, but their purpose is to transfer directly to a user essentially the same level of precision or accuracy achievable at a national laboratory in the making of a measurement that is needed for practical application in the research laboratory, on the production line, or in the marketplace.

For the metrologists who respond to these challenges the rewards can be very satisfying. NBS, for example, has found that beyond the original and primary purpose of improved measurements for marketplace equity, its results have been used in universities to improve instruction and research; in industry to stimulate new products, increased productivity, greater reliability in product performance, and new directions in research; and in other government agencies to reduce costs, and to improve significantly system reliability (1,2).

To illustrate how the National Bureau of Standards is responding to this challenge, this paper introduces some of the NBS activities in electrical and electronic measurements, and describes in some detail the work in semiconductor technology, giving a few examples of the transfer mechanisms used in disseminating the results of this work.

2. THE CENTER FOR ELECTRONICS AND ELECTRICAL ENGINEERING

The Center for Electronics and Electrical Engineering provides a focus in NBS for addressihg electrical, electronic, and electromagnetic materials, components, instruments, and systems. It provides well-documented and evaluated measurement methods, data, and interpretive theory; physical standards, traceability to these standards or measurement assurance programs; and associated technology and technical services. It provides these to government, industry, and the scientific community, ultimately benefiting the consuming public. Its emphasis is on solving measurement and standardization problems which are essential to equity in domestic and international trade; to control of manufacturing material, equipment, and processes by manufacturers and their customers; and to the applications of a number of other Federal agencies. The Center does not develop new products or processes, except where these may be required for its own measurement research, nor does it promulgate performance standards or specifications; these activities, of course, are the responsibility of industry or other Federal agencies.

The work of the Center has four principal programmatic thrusts (Fig. 1), each addressing closely-related technologies, a corresponding market, and technical and societal problems of current significance. These thrusts are in (1) Semiconductor Technology, (2) Fast Signal Acquisition, Processing, and Transmission, (3) Electrical Systems, and (4) Electromagnetic Interference. In this and the following two papers, examples from three of these areas will be described. Additional information about all of the Center's work is readily available, for example in an extensive collection of publications (3,4,5,6).

3. SEMICONDUCTOR TECHNOLOGY

Semiconductor devices and integrated circuits lie at the heart of the modern electronics revolution. Semiconductor technology is therefore central not only to electronics but to the economic and social health of modern industrial societies.

The semiconductor device industry provides extreme challenges for the metrologist. It deals with some of the purest and most perfect materials known to man and with microscopic and submicroscopic dimensions. It is concerned with trace impurities at concentration levels ranging from parts per trillion (parts in 10^{12}) to parts per million, with controlled variations in these concentrations which range over several orders of magnitude over a span of less than a micrometer; with dimensional integrity of tenths to hundredths of a micrometer; with circuit element densities of hundreds of thousands of devices per square centimeter; with signals in the gigahertz range; with currents in the picoampere range and less; and with a host of new processing technologies which involve the interaction of radiation with matter, plasma physics, photochemistry of polymers, etc. Despite the great success of this industry in providing new and sophisticated products, it has outstripped available metrology. New and refined techniques are essentia for use both in manufacturing control and in the marketplace. In response, NBS is conducting-a major program in semiconductor measurement technology comprising selected research topics in each of the six broad areas shown in Fig. 2.

DEFECT METROLOGY

Defect Metrology is concerned with measurements for the identification, characterization, and control of impurities and structural defects in silicon; and with the development and production af Standard Reference Materials (SRM's) needed to transfer measurement calibrations to the industry. The presence of selected impurities, intentionally introduced in carefully controlled densities and spatial distributions, gives an otherwise pure semiconductor crystal the desired properties of a controllable electronic device. On the other hand, other impurities and defects can have both beneficial and adverse effects on the performance of semiconductor processes and devices. They affect the brittleness and dimensional stability of silicon slices, electrical conductivity of the silicon, and the switching speed of devices, for example.

These important influences result from the presence of such entities in vanishingly small concentrations, from typically a few hundredths of a percent down to a hundredth of a part per billion (parts in 10^{11}), and from their uniform concentration in the crystal or their presence in micrometer-thick layers with many orders of magnitude changes in their concentration. Direct measurement at these concentrations is seldom possible, so the presence and behavior of the impurity or defect in question is inferred by measurement of their electrical or optical effects.

Resistivity is the most important electrical property used by the industry for material specification and control, and for device design and manufacture. Early NBS work with the American Society for Testing and Materials (ASTM) has led to improvements in precision of four-probe measurements by a factor of 10, provided the technical basis for five related industrial standards, and led to the issuance of three SRM's to calibrate 4-probe instruments. For those of us who are concerned with the importance of measurement science, it is interesting to note that the economic benefits of this work were estimated by the industry at over $30M (over 100 times the cost of the work) saved in marketplace transactions alone, and perhaps ten times this amount in manufacturing economies.

In follow-on work NBS modified and reissued one of these SRM's to be compatible with eddy-current instruments which measure resistivity of wafers. To relate resistivity measurements to the carrier mobility and dopant (that is, intentionally introduced) impurity density that device designers need to know, NBS research has led to new reference data now incorporated in another ASTM standard.

More recent work is addressing such topics as spreading resistance measurements used for resistivity vs. depth profiles in silicon structures (a set of four SRM's fore- and F-type materials with <100> and <111> crystal orientations will be issued in 1983); and improved measurement and understanding of non-dopant materials, such as oxygen and carbon.

The plot of Fig. 3 exemplifies how the presence of oxygen in silicon can be determined by measuring the optical absorption coefficient at an infrared wavelength of 9 µm (approximately 1100 cm-'), where silicon itself is virtually transparent. This absorption line results from interstitial oxygen. Oepending on the thermal history of the specimen, oxygen can affect the electrical conductivity or the brittleness of silicon, as well as other properties. It is present in amounts up to a few parts per million, near its solubility limit, and can be measured optically over a concentration range from that level down to about one percent of that level.

One difficulty in making this measurement arises from the nature of the Fourier transform infrared (FTIR) instruments that are widely used. These instruments measure the Fourier transform of the absorption spectrum and manipulate the information digitally to produce a measure of the absorption coefficient. The computer algorithms used in instruments of differing manufacture are not the same, and the absorption coefficients that result do not always agree either among FTIR instruments of various makes or with measurements made on older, dispersive instruments. Under the auspices of an ASTM task force chaired by a member of NBS, the manufacturers of FTIR spectrometers have been willing to reveal their algorithms and are working to find the sources of the differences in the measurements and to determine whether or not NBS needs to provide reference standards. This is a particularly timely effort because the Semiconductor Equipment and Materials Institute (SEMI) is presently trying to establish standard levels of oxygen in silicon in their silicon materials specifications, specifications which are rapidly achieving worldwide significance. Accurate and repeatable measurements are thus needed very soon. NBS staff are active in this SEMI work as well.

In keeping with silicon's leading role in the semiconductor industry NBS work emphasizes this material. However, compound semiconductors, such as gallium arsenide, have unique applications for light-emitting devices and semiconductor lasers, both vitally needed for fiber-optic communication systems, for discrete semiconductor devices useful at microwave frequencies, and for very fast integrated circuits. Recent advances in the production technology for gallium arsenide have greatly improved the economics of such applications and substantially increased marketplace sales of this material. Consequently we have recently undertaken a study of the measurement needs in this field which may need NBS attention.

PROCESS METROLOGY

The Process Metrology work is now aimed at developing measurement techniques for characterizing thin insulating films typical of those used in integrated circuit manufacture. The properties of these films are crucial to proper operation of metal oxide-silicon (MOS) devices, the largest class of integrated circuits, including most memory and micro-processor devices for example, and have important effects on most other kinds of semiconductor devices as well. An advanced research ellipsometer is under construction to provide a state-of-the-art optical tool for this work (7). Theoretical error-analyses done in connection with the design of this instrument have already identified opportunities for improving measurement accuracy of commercial instruments. Two different oxide thickness SRMs will be calibrated with the research ellipsometer, as one of its applications, to assist in realizing these improvements.

DIMENSIONAL METROLOGY

Dimensional Metrology in this program comprises the development of measurements of linewidth to high accuracy over the range from 10 µm down to 0.5 Pm and. ultimately, to 0.1 pm. Dimensions of the smallest circuit feature are one of the essential variables in integrated circuit design; they influence nearly all of the performance characteristics of integrated circuits, but particularly their speed. These dimensions must be carefully controlled throughout the manufacturing process. NBS work since 1975 has focused on optical linewidth measurements on photomasks as one key commercial metrology problem [See Ref. (6), Micrometrology, pp 21-22]. In this work, we have extended the theory of optical microscopy. The development of this theory and its implementation in measurement procedures and prototype measurement instrumentation, coupled with dissemination efforts including the issuance of two SRM's and workshop training to some 300 people, have greatly improved accuracy in industrial linewidth measurement. Nearly all domestic IC manufacturers have adopted the NBS procedures. Industry has developed new instrumentation, rewritten microscope instructions, produced secondary standards for sale, reduced systematic errors found in all manufacturer's measurements (typically of the order of tenths of a micrometer), and enjoyed improvements in device manufacturing productivity (e.g., by 30 percent in one case).

Figure 4 suggests how the measurement is done, and why the accuracy of the measurement has been so greatly improved. The solid line is a measured trace of light transmission as the edge of a dark-chrome-on-glass pattern, such as that on the NBS linewidth SRM, is scanned across the axis of the optical system used to calibrate the SRM. The points on the curve are calculated without adjustable constants from a comprehensive mathematical model that includes the optical system, the object, phase changes at material interfaces, and the coherent nature of the illumination. The details of the trace are fully accounted for. In addition, the physical edge of the line has been shown from this analytical treatment to be at 0.25 of the rise of the trace from the minimum to the maximum asymptotes of the curve, further reducing the error in identifying the edge.

Each of the lines on the SRM (Fig. 5), ranging in width from 0.6 to 10 µm, is calibrated with a repeatability of 0.01 µm (1 σ) and with a certified accuracy of 0.05 µm. This is entirely adequate for optical linewidth measurements of dark chrome patterns on glass photomasks for several more years, if the present trends in the rate of reduction of the size of IC geometries are maintained. Additional bright-chrome-on-glass SRMs will be available in the near future, to cover further the needs for photomask measurements.

There is a pressing need for similar measurements of linewidth of patterns on silicon wafers. These patterns are thicker than chrome-on-glass layers and they have edges with varying profiles. As Fig. 6 shows, the modeling of this measurement is much more difficult than for that of lines on photomasks. This problem is being addressed now, and a prototype SRM for calibration of wafer linewidth measurements is being fabricated. If all goes well, a useful SRM will be available in about a year.

Many semiconductor firms are using scanning electron microscopy for linewidth measurement, or are both fabricating images and examining them with electron beam equipment. There are at present no suitable calibration tools for this measurement. The problem is under study and SEM equipment is being procured to allow NBS to address this measurement issue as well. It is hoped to extend the industry's ability to make accurate linewidth measurements to lines of about 0.1 µm width before such small geometries are required for production devices.

DEVICE AND PROCESS MODELING

The complexity of state-of-the-art integrated circuits and the very large scale integrated (VLSI) circuits under development makes an experimental approach to design and fabrication increasingly costly. A computer aided approach, relying on the application of device and process models of verified acuracy, can significantly reduce costs. Adequate models are required to reduce design time, to evaluate new designs before commitment to fabrication by the manufacturer, or to purchase by a customer. Important to the metrologist is the fact that these models are also key in developing an adequate measurement capability, both for identifying the appropriate measurable quantities and in interpreting new measurement techniques.

The current objectives of the Device and Process Modeling work are to develop documented and verified models of "short-channel" MOS transistors for VLSI, to develop and document low-temperature process models for fabricating transistors for VLSI, to use the models to identify the measurable quantities and related accuracies required as model inputs, to calculate the quantities that are critical for design and performance assessment, and to identify measurement procedures necessary for verifying model performance for key semiconductor technologies. Under development is a hierarchical package for solving three coupled nonlinear elliptic partial differential equations in two dimensions in order to analyze the currents and fields in state-of-the-art semiconductor devices. In addition, profiling techniques for obtaining data for process models using secondary ion mass spectroscopy and scanning electron microscopy are being examined. Calculation of initial distributions of ion-implanted dopants in two dimensions and the subsequent redistribution of the dopants over a wide range of processing variables is in progress.

The first major software product of this work has recently been released. This is a device physics code called CS1 which is primarily directed at short-channel MOSFETs (MOS field-effect transistors). This code relates device fabrication and physical characteristics to the expected device electrical characteristics. The code, based on a two-dimensional charge-sheet model for MOSFETs (8), solves the electrostatic potential in silicon using two-dimensional finite elements; it solves for the potential in the oxide using a fast Poisson method; and it solves for the electron current in the channel by computing an average quasi-Fermi level at points down the channel using analytic quadrature. Figure 7 gives the measured characteristics for a device with a 1.89-µm channel and 10^{15}-atoms/cm^3

channel doping. The device exhibits short-channel behavior. A set of curves from standard one-dimensional theory and set of curves resulting from simulating this device with CS1 are also shown on the figure. The improved accuracy of CS1 is obvious. Since this code was released in August, magnetic tapes and user manuals have been distributed on request to more than 75 organizations including industrial concerns, government laboratories, and universities.

INTEGRATED CIRCUIT TEST STRUCTURES

Large-scale integrated circuits are too complex to permit complete functional testing. It is common practice to rely on a combination of selected functional tests and process-control tests to give assurance of uniformity once an acceptable product has been achieved. Test structures are important for these latter tests.

Integrated circuit test structures are solid-state devices which are fabricated by the same processes (and often at the same time) as product integrated circuits. These test structures are designed to permit measurement of selected material, process, device, or circuit parameters by means of electrical tests. They can be used to evaluate process uniformity, to measure device and circuit parameters for modeling and performance assurance, and to evaluate the performance of processing equipment. They are vital to success in manufacturing and can play a key role in the marketplace exchange of devices (9,10).

NBS work in Integrated Circuit Test Structures is providing test structures and associated test methods of a practical and generic nature that are unambiguous in their measurements and well documented for use by both manufacturers and their customers. Recently, research efforts have been directed toward structures appropriate for electrically measuring the linewidth of conducting layers, for determining contact resistance, for evaluating electromigration and latch-up susceptibility, and for extracting propagation delay data.

A deceptively simple example which illustrates NBS efforts to improve test effectiveness is a structure for the direct measurement of interfacial contact resistance. As the critical feature size of semiconductor devices decreases, the major dimension of the metal-semiconductor contact regions, of the order of micrometers to tens of micrometers, also decreases, causing an increase in the resistance encountered as current passes between the metal and semiconductor. Problems are also encountered with the metallurgies and processes needed to produce reliable, low-resistance contacts to regions with shallow junctions. Because of these factors, the quality of the metal-semiconductor contacts will have an increased influence on the performance and reliability of integrated circuits. The electrical nature of the contact region is usually described in terms of interfacial contact resistance, defined as the total resistance of the metal-semiconductor interfacial layer encountered as current is forced from one layer to another. One needs to know both the total resistance and the spatial uniformity of the contact resistance.

The four-terminal test structure shown in Fig. 8 allows a direct Kelvin measurement of the total, or interfacial contact, resistance. The measurement consists of forcing a known current from probe pad 1 to probe pad 3, that is from the diffusion level through the contact to the metal level. Voltage is measured between probe pads 2 and 4 by means of the voltage taps which are orthogonal to the direction of current flow through the contact (11).

Two-dimensional mathematical modeling of the structure and experimental verification were carried out to demonstrate, first, that the Kelvin design avoided the sensing of probe-to-probe pad resistances and the probe-pad to contact region resistance in either the diffusion or metal layers and, second, that design of the diffusion-level current and voltage taps to be equal in width to the contact window eliminates troublesome parasitic resistance otherwise associated with current pinching as current passes from the current tap into the contact window.

Assurance that the resistance measured by this structure was in fact the true value of the contact resistance was achieved by an intercomparison of the results from such a structure with those from a variety of other and more complex structures sensitive to contact resistance and other properties. All these structures were included on a test chip, which allowed the structures to be fabricated simultaneously during a single process run on a wafer for the intercomparison.

The spatial uniformity of the contact resistance can be investigated by measurements using several of the interfacial contact resistance test structures, each having a different contact window area from the others. An example of the results for a well processed, uniform contact using aluminum/silicon metallization is shown in Fig. 9. Measured interfacial contact resistance (shown on the ordinate as the ratio of measured probe voltage and current) is plotted against contact window area for square windows ranging from 2.5 µm to 20 µm on a side. A least-squares fit of the data shows a linear relation as expected.

A similar set of measurements for 100-percent aluminum metallization yielded the non-linear relation shown in the figure. Visual inspection of the contact area on these devices with the metallization removed showed a high degree of physical non-uniformity along the periphery of the window, attributed to the dissolution of silicon into the aluminum during the sintering process and the subsequent recrystallization of the silicon at the aluminum-silicon interface upon cooling.

Research on test structures for contact resistance is continuing to determine the range of validity for smaller contact windows, alternate metallurgies, and for contacts other than between silicon and metal. NBS-developed test structures, and test-chip designs of selected structures appropriate to evaluation of particular technologies, their basic principles, and detailed procedures for application have been transferred to the semiconductor community through a variety of publications and through provision of mask-making tapes for their convenient implementation.

DEVICE METROLOGY

Just as the revolutionary changes in semiconductor technology have affected the materials, design, processing, and electrical properties of devices, so have they affected packaging and thermal properties. Packaging and thermal problems are limiting factors in advances in very large scale integration. They reflect effects of the large size of the semiconductor chips, the greatly increased number of leads, greater effects of the package on electrical performance, and higher thermal dissipation of the densely populated chip. NBS work on Device Metrology is currently addressing nondestructive measurement methods for VLSI chip-to-package and lead-to-chip bonding integrity and VLSI package thermal properties. In addition it addresses thermal property measurements for power devices. Power devices, which meet the ubiquitous requirement for efficient power control and conversion, have long suffered from the need for improved thermal property measurements. The emergence of MOSFET devices, to supplement the widely used bipolar devices, has introduced new unknowns in the measurement field.

The temperature of the electrically active region of a device, the "operating temperature" is important in determining the reliability and operating life of the device, and it also has a strong influence on many electrical parameters. A usually-specified property i-elating the temperature of this microscopic and inaccessible active region to conveniently measured parameters is thermal resistance. This is the difference between the active region temperature and that of a specified reference point, divided by the power dissipated in the device. Usually, temperature-sensitive electrical parameters are used to determine thermal resistance, and thus "measure" the operating temperature. At NBS, the result of temperature measurements using three different such parameters suitable for power MOSFETs have been examined and compared with the temperatures of the surface close to the active region determined using an infrared microradiometer (12). These parameters were: the source-gate or threshold voltage measured at a low-level drain current (VSG), the forward voltage of the drain-body diode (V_{DB}), and the device on-resistance ($R_{DS}[on]$).

Examples of calibration curves for these parameters are shown in Fig. 10. The results of temperature measurements on several devices for a number of electrical operating conditions using the three parameters as well as the infrared microradiometer are given in Table I. All these parameters show reasonable agreement with the infrared microradiometer and can be used to determine the device operating temperature. The threshold voltage (VSG) most closely tracks the infrared measurements: this is not unexpected since VSG senses the channel region, the region nearest the device surface. Note that there are a number of different operating conditions which yield the same power level. These sensors indicate little variation in temperature showing that the temperature measured is not very dependent on the operating conditions used to obtain a given power dissipation. This is very different from the situation reported earlier by NBS for bipolar device dissipation where the temperature in the active region is not uniform and the peak temperature is very much a function of operating conditions. The details of this new work on power MOSFET temperature measurements are being incorporated into an Electronics Industries Association Power MOSFET Handbook to provide recommended procedures for determining device temperature.

Early NBS research on thermal properties has already found its place in industrial and military standards and the current work is providing a basis for the issuance of standard reference materials for calibrations of thermal resistance measurements, and for test structures for determining the thermal properties of VLSI and power device packages (13).

CONCLUSION

This paper has given an indication of some of the demands of one rapidly advancing technology, semiconductor technology, on measurements for dimensional, electrical, thermal, and other physical properties of semiconductor materials, devices, and circuits; demands that go beyond those traditionally addressed by metrology organizations. It has provided a few examples of NBS work to give an indication of the way one laboratory dedicated to metrology is responding to the exciting opportunities to provide new methods, physical standards, and services to meet the practical needs of science, industry, and governmental functions.

ACKNOWLEDGEMENT

The authors would like to acknowledge the technical contributions of the staffs of the Semiconductor Devices and Circuits Division and the Semiconductor Materials and Processes Division which served as the examples found in this paper.

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Table I
Temperature Measurement Data from Specimen Devices;
Measurements Made Using Temperature-Sensitive Parameter Techniques and Infrared Microradiometer

Device Number	Operating Conditions $I_D(A)/V_{DS}(V)$	Temperature Rise Above Case (°C) IRM	V_{SG}	V_{DB}	$R_{DS}(on)$
1	1.0/30	33.5	31.0	28.8	25.7
	1.5/20	33.5	31.0	28.8	26.6
			31.0	27.8	28.0
2	0.5/60	38.0	35.0	36.5	33.4
	1.0/30	38.0	35.0	36.1	32.2
	1.5/20	38.0	35.0	36.1	33.2
3	1.0/60	80.0	80.3	70.7	69.2
	1.5/40	80.0	80.3	70.4	68.6
4	0.5/60	37.0	36.8	36.1	33.0
	1.0/30	37.0	36.8	36.1~	35.0
	1.5/20	37.0 .	36.8	35.0	35:0
5	1.5/40	73.0	69.0	62.0	56.0
6	1.0/20	34.3	31.4	28.1	28.2

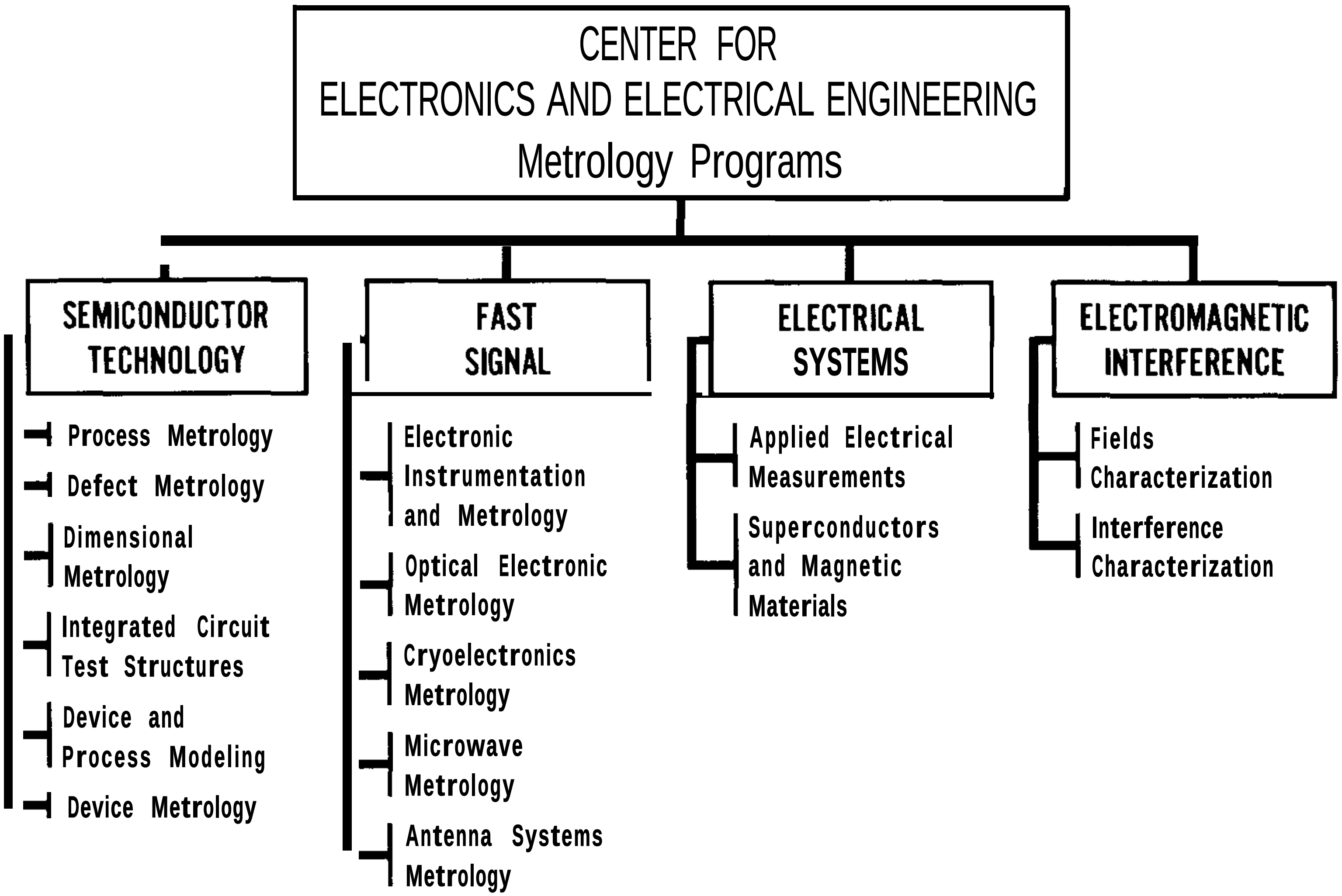

Figure 1. Programmatic thrusts in the NBS Center for Electronics and Electrical Engineering

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SEMICONDUCTOR MEASUREMENT PROGRAM

- Defect Metrology
- Process Metrology
- Dimensional Metrology
- Device and Process Modeling
- Integrated Circuit Test Structures
- Device Metrology

Figure 2. Research topics in the NBS Semiconductor Measurement Program.

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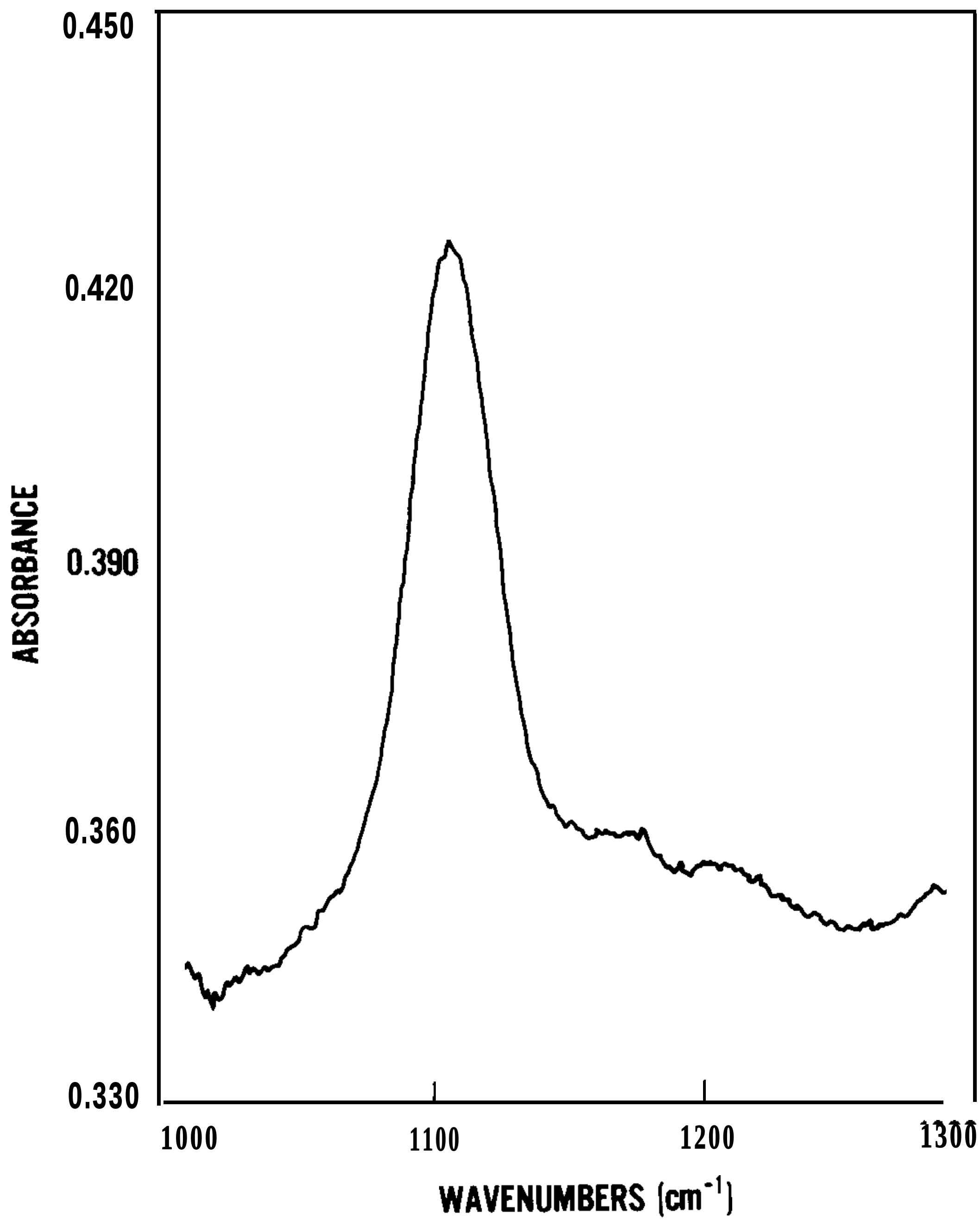

Figure 3. Fourier transform infrared spectrometer plot of the absorbance [arbitrary units) as a function of optical wavelength [expressed as wavenumbers) for a specimen silicon wafer having one polished and one lapped surface.

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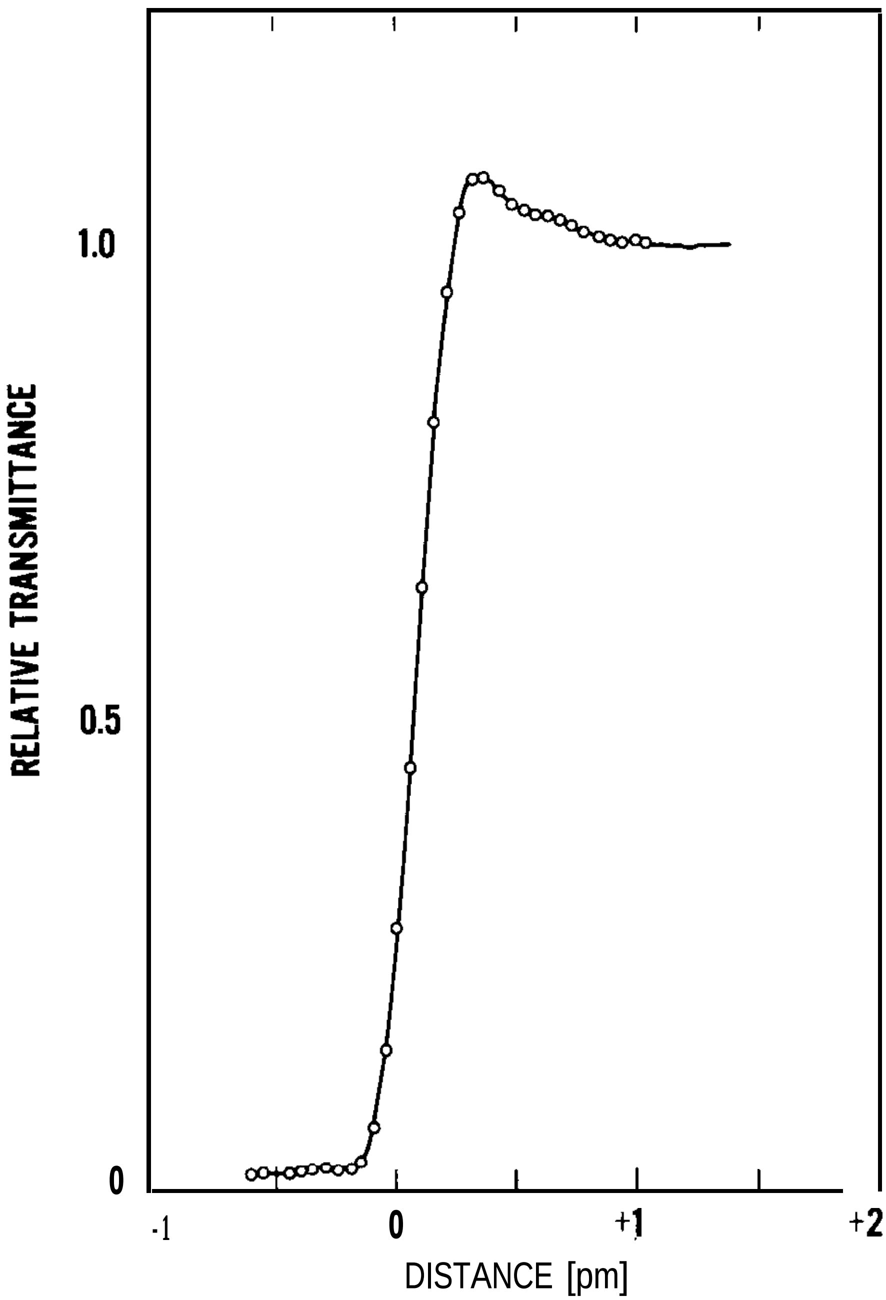

Figure 4. Measured trace [**solid** line] and theoretical plot [circles] of relative transmission [arbitrary units] as a function of distance [micrometers] as the edge of a dark chrome line on glass is scanned across the optical axis of the NBS reference microscope.

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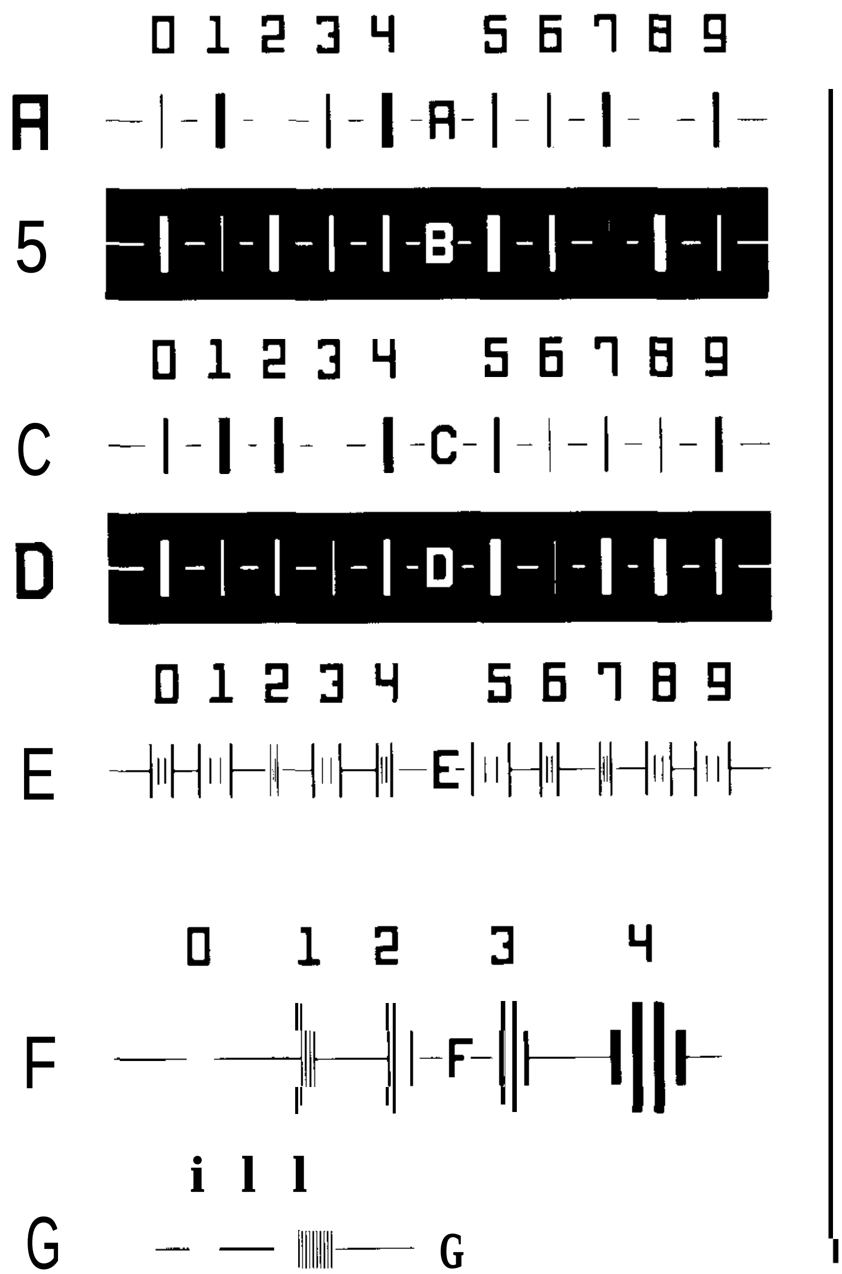

Figure 5. The line pattern used in Standard Reference Material 474, **Anti**-Reflective Chromium Photomask Optical Microscope Linewidth Measurement Standard. Rows A through 0 are for calibrating measurements of linewidths of opaque and clear lines on reverse polarity backgrounds over the approximate range 0.5 to 12 micrometers.

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MODEL LEVELS

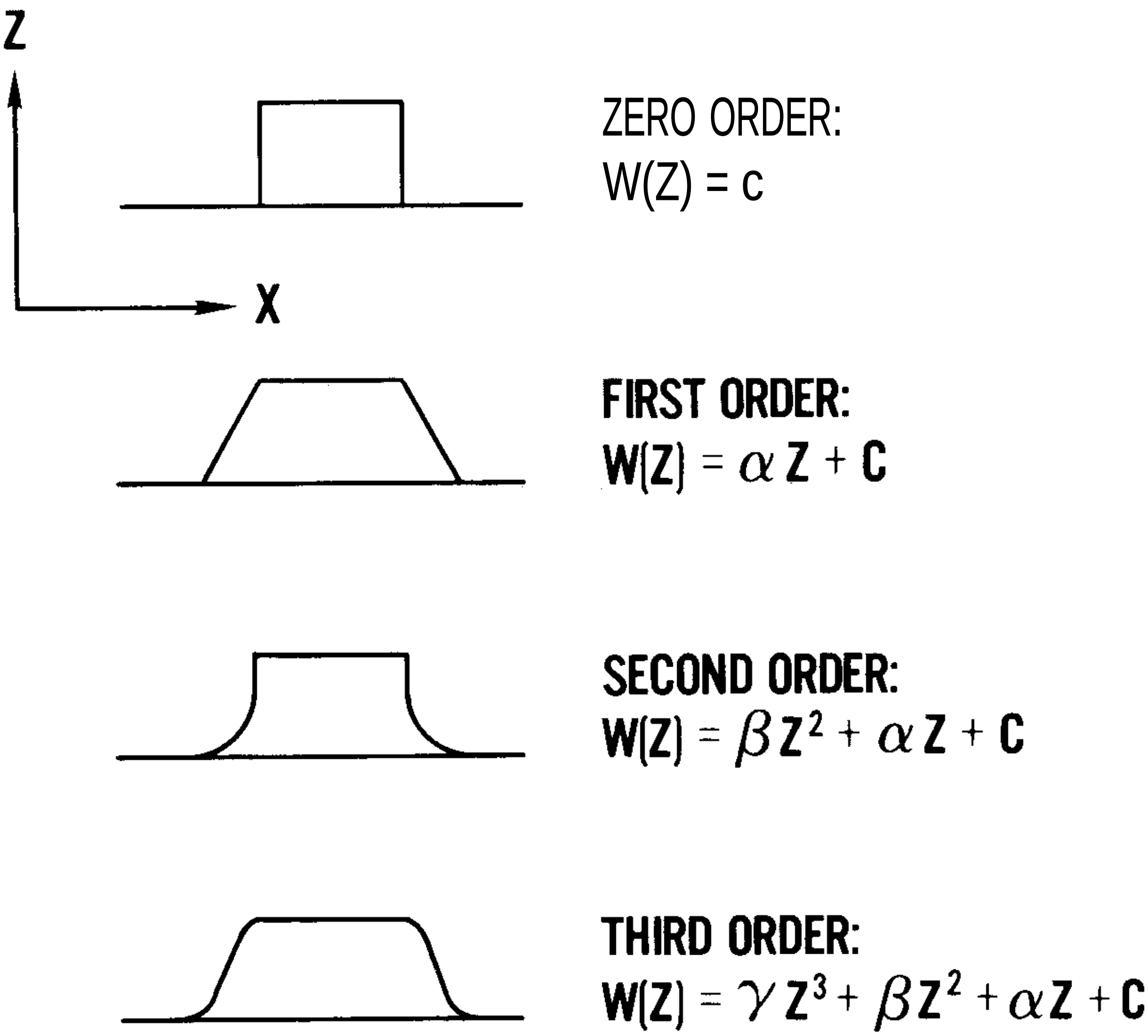

Figure 6. Deviation from "ideal" rectangular line cross section increases complexity of models for linewidth measurements on silicon wafers.

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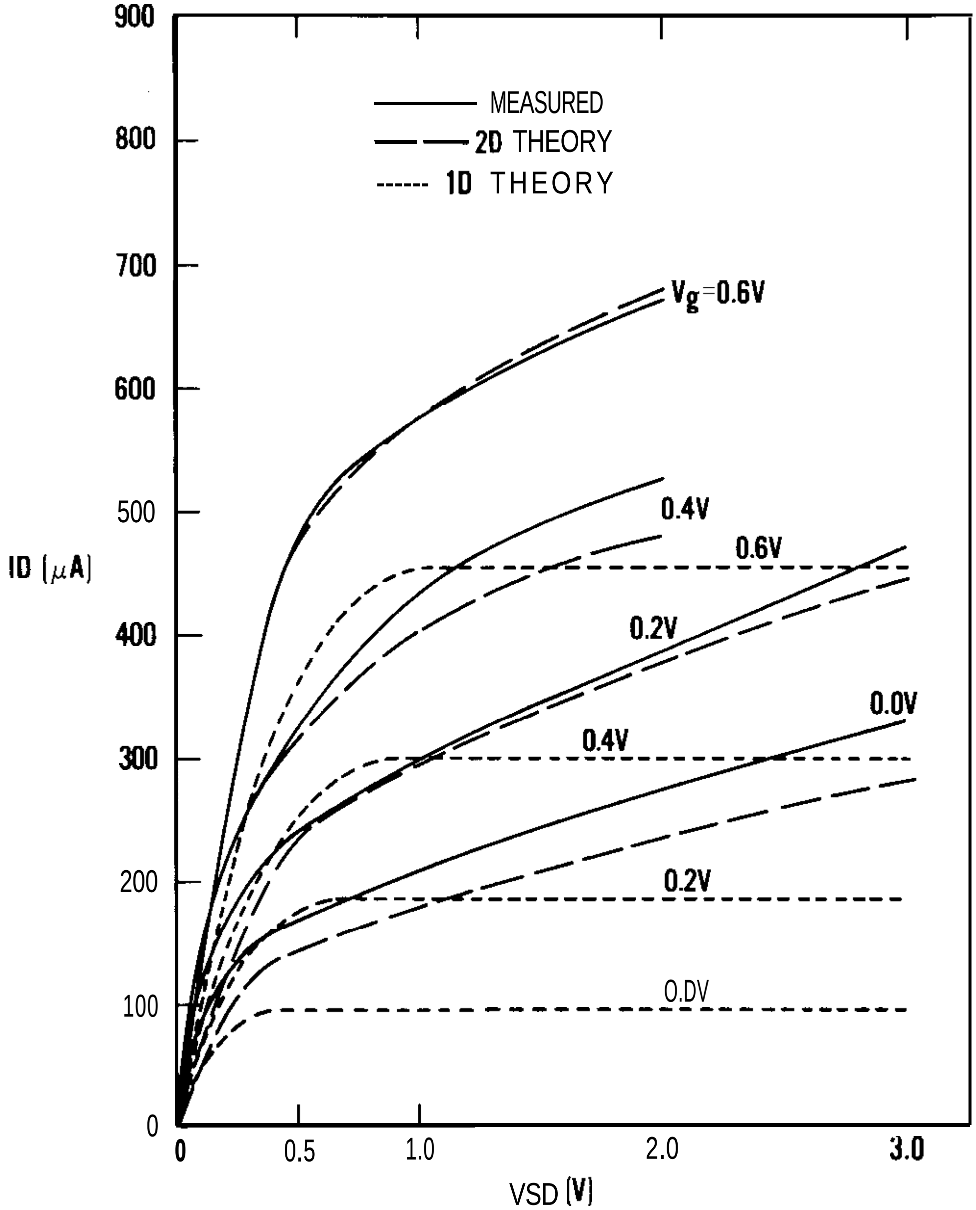

Figure 7. Source-drain voltage [volts] as a function of channel current [microamperes] for a metal oxide-semiconductor field-effect transistor having a 1.89-micrometer channel and channel doping density of 10^{15} atoms/cubic centimeter. The improved agreement between measured results [solid lines] and two-dimensional predictions [short-dash lines] contrasted with one-dimensional predictions [long-dash lines] is dramatic.

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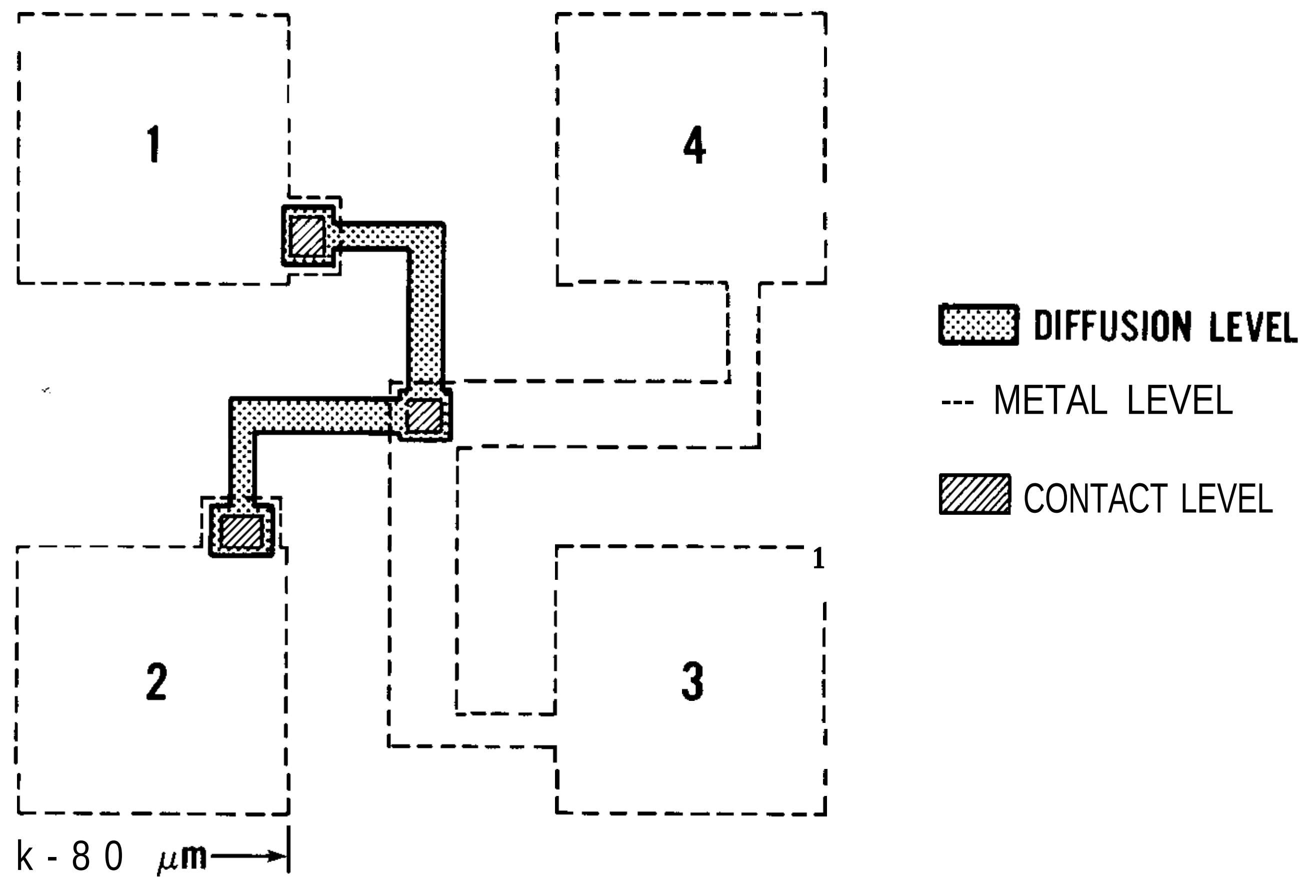

Figure 8. NBS integrated circuit test structure for measuring interfacial contact resistance by Kelvin methods.

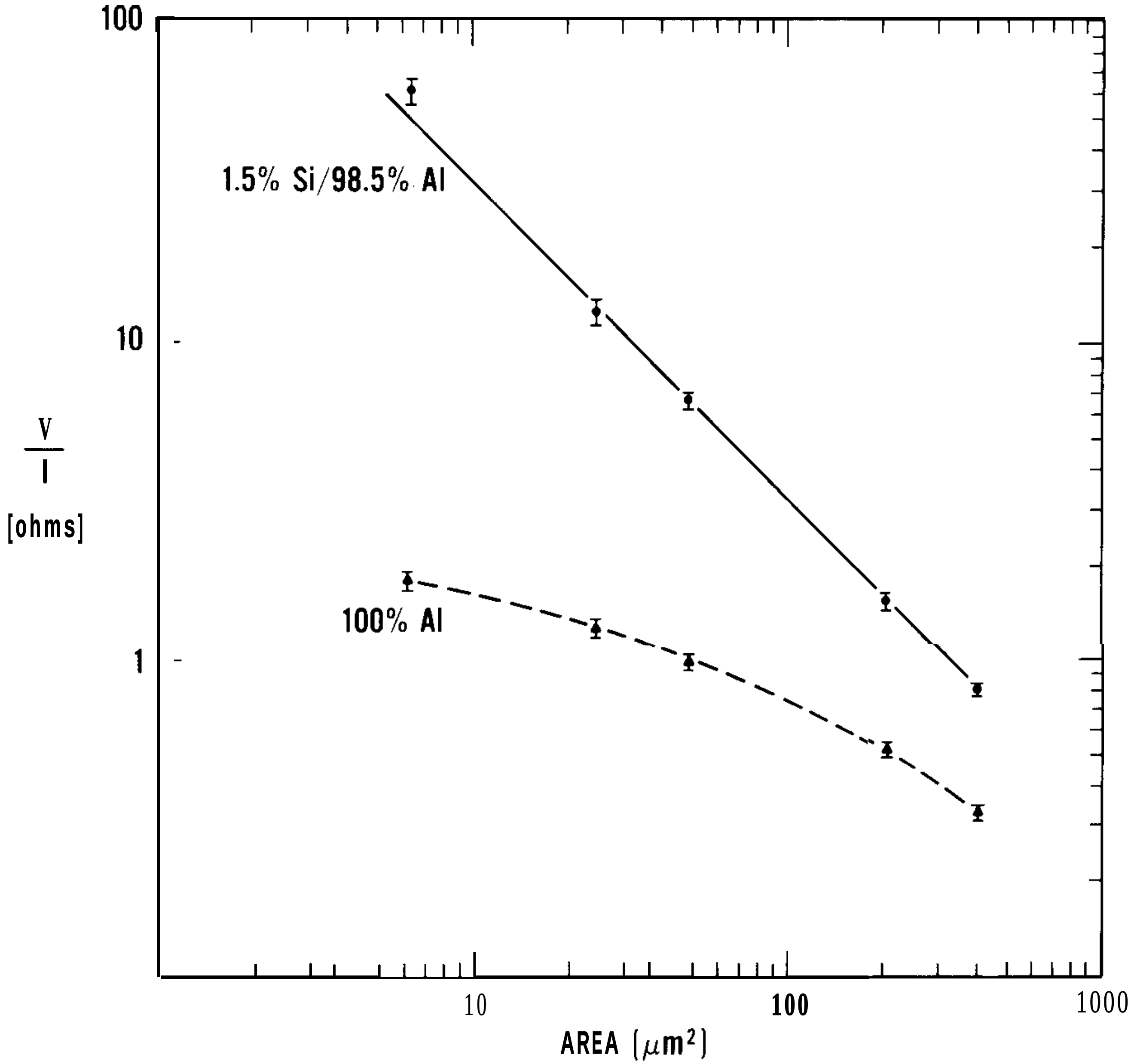

Figure 9. Results from the test structure of Figure 8. The plotted points represent measured values of interfacial contact resistance [ohms] as a function of contact window area [micrometers squared]. Linearity and nonlinearity are discussed in the text.

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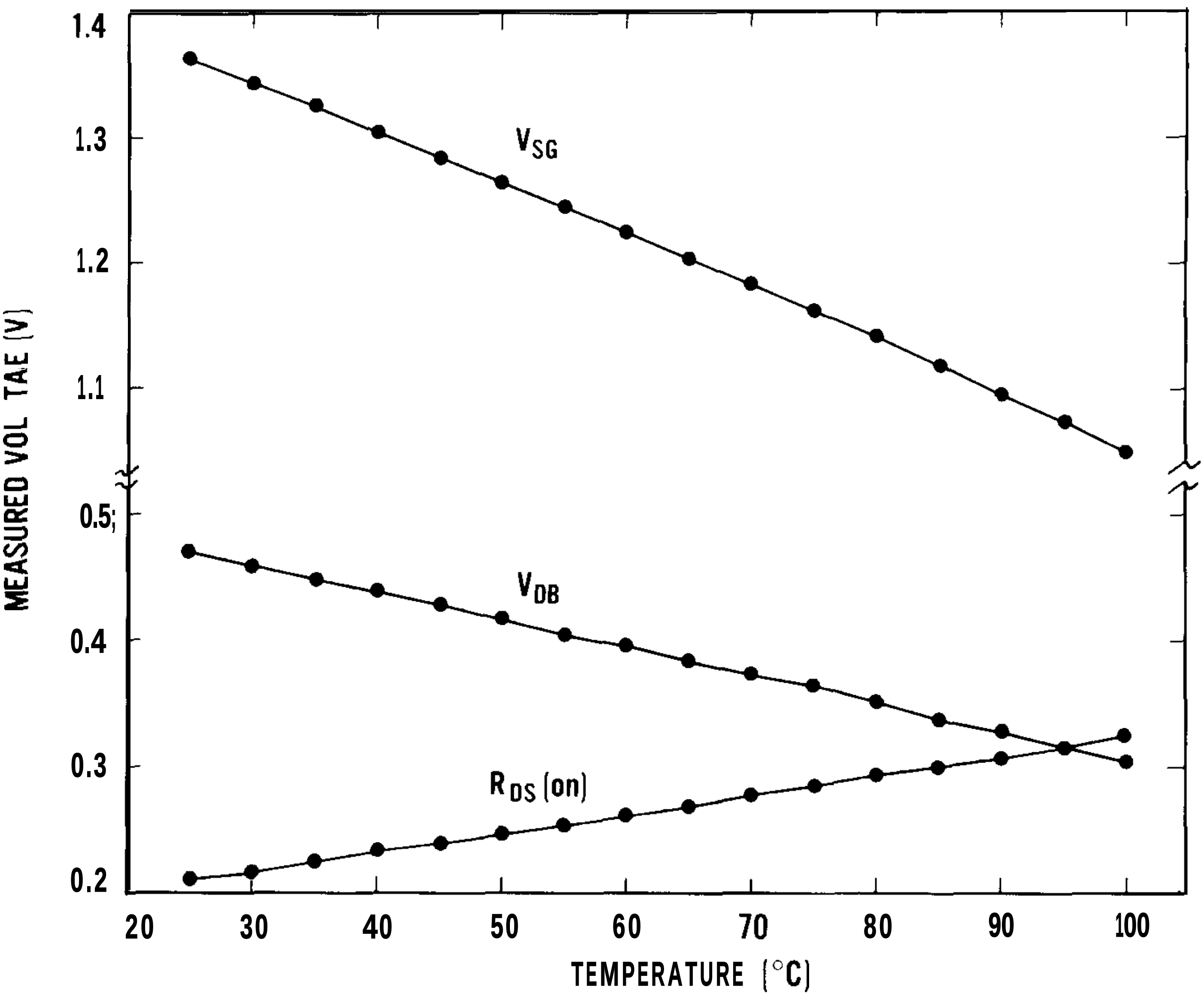

Figure 10. Calibration curves for measurements of power device temperature (degrees Celsius] from temperature-sensitive parameters (volts]. The parameters are identified in the text.

NBS/CEEE/DEC 82

THE MI MEASUREMENT CHALLENGE*

C. K. S. Miller
Electromagnetic Fields Division
National Bureau of Standards
Boulder. Colorado 80303

Abstract

With the increasing proliferation of radiating sources to the electromagnetic (EM) environment and the increased use of semiconductor technology in consumer and industrial products, incidents of electromagnetic interference (EMI) to electronic products have increased. Current EMI measurement difficulties are reviewed and a description is given of the National Bureau of Standards' (NBS) measurement research, both planned and in process.

Key words: Compatibility; electromagnetic environment; electromagnetic interference; EMC; EMI; EMI testing; measurements.

Introduction

Today we are seeing electronics moving into our lives in ways that would hardly have been dreamed possible 30 years ago. Electronics are in our automobiles and homes--in the washers, dryers, cooking ranges, security systems--besides the more commonplace televisions, radios, hi-fi/stereo centers, and telephones. The younger generation at-a taking as a matter of course the electronic games, watches, calculators, personal computers, digital clocks, and cameras that the older generation are continually amazed at.

The growth in the semiconductor industry has made possible the advances in applications of electronic devices and has paralleled the increase in the incident electromagnetic (EM) radiation. Electronics is applied to products that emit EM radiation, either intentionally or unintentionally. The growth in intentional radiators for commercial broadcast stations and private use, such as citizen band and amateur radio, has been significant since World War II (1)--not to mention many other man-made sources such as radars, intrusion alarms, garage-door openers, navigational beacons, mobile radio (for land, marine, and air communications), satellite communications and military systems. There has also been a growth in unintentional radiation from industrial heaters and sealers, microwave ovens, medical diathermy equipment, arc welders, internal-combustion engines, electric motors, and make-and-break switches.

These two elements comprise the essence of the electromagnetic interference (EMI) problem; that is, if our electronic components and systems could not be interferred witn or if there was no source of radiation to cause the interference, there would be no EMI problem. The difficulty is that semiconductor electronics is more susceptible to EMI than tube-type electronics and there is a greater incidence of electromagnetic radiation that can cause the interference. While most electronic designs employ digital approaches to increase their immunity, interference still occurs to both analog and digital circuitry electronic components and systems. Better testing methods are needed based on sound measurement theory and practice.

It is the intent of this paper to present an overview of the EMI measurement problem caused by radiated energy and to describe some of the efforts being made by NBS to provide a metrology base from which to attack the problem.

The MI Measurement Problem

1. The EM Environment

To assure that any electronics is immune to the local electromagnetic environment, we need to test the electronics in just such an environment to validate its immunity. Such a requirement means that we (1) have a priori knowledge about the EM environment, and (2) have adequate test methods to reliably determine immunity. This is where the measurement problem lies--for on the one hand, our methods of characterizing the EM environment are crude and inadequate and on the other hand, reliable and repeatable testing methods are not being employed in general. Let us look at this matter a bit more carefully to appreciate the difficulty of the task and to see what new approaches and research are needed.

The EM environment is generated by EM waves resident in the environment. The EM wave is defined by the IEEE as "A wave characterized by variation of electric and magnetic fields (2)." An example of a simple electromagnetic wave is shown in figure 1. Here can be seen the two co-existing parts: an electric field denoted in the figure by the solid line and a magnetic field denoted by the dotted line; they exist in two planes perpendicular to each other and perpendicular to the direction in which the wave is traveling, denoted by the arrowhead on one end of the wave. The characteristics of the wave are embodied in the electric and magnetic fields. An electromagnetic wave is multidimensional and a very complex phenomenon.

The parameters associated with EM waves that affect the environment include direction, time, frequency, pattern, spatial coordinates, distance from radiating signals, power (amplitude), polarization, waveform, number of signals, and interaction with local materials. Figure 2 is a representation of some of these parameters. The figure shows two cuts through the time, amplitude,, and frequency space. The figure shows that at a single frequency, amplitude can vary with time; whereas at a single instance in time, amplitude can vary with frequency. It is necessary to look in all directions if the EM environment, at a point, is to be understood. While each of these parameters can be demonstrated independently (1), it is beyond the scope of this paper to illustrate them.

Besides the multiple parameters associated with an EM wave, we must consider the shape of the wave, which changes depending upon the distance from the source. Figure 3 indicates three zones. In the zone called the Far Field, the EM wave is far enough from the source that, it has essentially become a plane; that is, the wave, if you could see it, would look like a sheet moving through space. This is why the shadow of an airplane, flying at any altitude, cast onto the earth is the same size as the airplane itself. In this example, the light from the sun is a plane wave and as the airplane breaks the plane wave, a shadow (or absence of light) is cast onto the ground. In the zone called the Intermediate Field, the EM wave is expanding as it moves away from the radiating source. These EM waves are like ever-increasing spheres. You can see this expanding effect when you cast a finger or hand shadow on the wall of a room using a candle flame as your source of light--the hand breaks the expanding EM wave of light and a large shadow is cast onto the wall. In the zone called the Near Field, the EM wave is not fully developed and the wave of figure 1 has not formed properly, so it is very difficult to predict what is happening in this zone at a particular point.

EMI problems differ depending upon which of these three zones you are in relative to the radiating source. Of course, you could easily be in the far field of one source and the near field of a second source. Usually, we are exposed to a number of sources simultaneously. We know how to measure the EM environment in the far field. However, if we use equipment designed to measure in the far field in the other two zones, we get erroneous results. If a number of objects exist in the path of the EM wave, the wave will bounce around--just as light does from light-colored objects and mirrors. This will disrupt the wave and artificially generate conditions similar to those encountered in the near-field zone, which makes it difficult to predict the energy at any particular point in space. The complications introduced by shadowing, reflecting, and focusing effects, and other phenomena not discussed make contending with interference a difficult problem at best.

The conglomeration of electromagnetic waves traveling in all directions from all manner of sources, both continuous and intermittent, with varying modulations, complex waveforms, and of multiple frequencies comprises the EM environment. It is such an environment that must be characterized and yet, traditionally, we measure the environment by making a slow scan of the amplitude as a function of frequency with antennas capable of meaningful far-field measurements only. Obviously, new methods are needed to quantify and characterize the EM environment that will describe its dynamic nature in both the near and far fields.

2. Interaction of EM Waves and Devices

Since electromagnetic waves are by their nature complex, it is difficult to understand the interaction of these waves with electronic devices. The degree to which an electronic device is interfered with is dependent on the complexity of the wave and the interaction phenomena encountered. A simple representation of the types of interaction is shown in figure 4.

If a straight piece of wire intercepts the EM wave, it will pick up the varying electric field of the wave and induce a varying signal on the wire. The signal placed on the wire by this process will be superimposed on whatever signal the wire was already carrying. Figure 4 shows a straight section of wire connecting two boxes containing electronics where the wire is providing a channel of communication between the boxes. With the superimposed signal on the existing communicating signal, the original communicating signal is impaired resulting in a potential electronic malfunction.

Similarly, if a piece of wire forms a loop of some sort with appropriate dimensions to match it with the dimensions of the EM wave, it will intercept and pick up the magnetic field of the electromagnetic wave and, in turn, impose a varying signal on the wire, figure 4. This signal will also be superimposed on the signal being carried by the wire and, in a similar way, can cause the electronics to malfunction.

Electronics, as used in most general applications, have wire connections. Wires bring ac power to the electronics. Wires connect electronics to sensors for information input, to controlling systems, to other pieces of electronics, and to readout or display devices. In semiconductor devices, very small wires are used to make connections for ingoing and outgoing signals into the vital chips themselves. Computers are made of a collection of electronic packages properly connected together to function on demand to perform their varied tasks. Even the electric-power transmission lines themselves intercept electromagnetic waves which are then superimposed on the ac power.

Similarly, electronic packages may have to be shielded to protect them from the EM environment. The shielding integrity is compromised if a slot or crack in the shielding case is of the appropriate dimensions to permit the electric field to be coupled into the case. In a similar way, holes left in a case of appropriate dimensions can permit magnetic fields to be coupled into the case.

While the above explanation suggests the rationale for engineering solutions to minimize electromagnetic interference, there is a significant void in our understanding of the phenomena at the semiconductor chip level. The phenomena associated with electromagnetic interference are so complex that there has been very little theoretical work attempted. This has led to the practice of solving EMI problems from an empirical base only, which, in turn, has caused wide bounds to be put on the measures associated with EMI.

3. Measurement Methods for Testing

Prior to specifying the test conditions for the electronic equipment, some knowledge of the anticipated EM environment for the future environmental setting of the equipment is needed. In some cases, such as for automobiles, very little can be known of the EM environment into which the electronics is immersed without an extensive survey of the kind made by the Environmental Protection Agency (3). As in the case of the Department of Defense (DoD), specifications of general test conditions are generated for uses such as MIL STD 461 where gross estimates are made to blanket the EM environment of the applications of the electronics equipment. But for most industrial and consumer uses of electronic equipment, little knowledge of the appropriate EM environments exists.

The primary tools used to measure the EM environment are antennas whose antenna factor is calculated or calibrated for plane-wave or free-space (that is, far-field) use. Yet the environments that surround electronics equipment is primarily near field, or near-field like, in nature. Further, the EM environmental measurements typically scan for amplitude as a function of frequency information. Consequently, the specifications used for testing may not represent the actual environmental conditions.

There are many testing methods for electronic devices and systems available to both characterize the emission from electronic equipment as well as its immunity to EM waves. These techniques may include measurements in the open field with earth or with metal ground planes, the use of shielded enclosures, anechoic chambers, parallel plates, transverse electromagnetic (TEM) cells, Helmholtz coils, etc.; all of which have their limitations in respect to frequency range, field uniformity, accuracy, availability, and cost.

A comparison of 20 different measuring techniques showing the complexity of the problem has been made by M. L. Crawford (4). Generally, many of these techniques are not adequate for two reasons: (1) they are not sufficiently understood technically as regards interpretation of the results obtained and (2) not all EM measurement parameters can be assessed with them. In fact, the repeatability and reliability of these techniques, for the most part, do not warrant the degree of confidence placed in them. Further, I am not aware of any methods that can test at more than a single frequency at a time with the exception of electromagnetic pulse testing facilities.

In general, the most common practices use shielded enclosures because of the military specification requirements. The repeatability of measurements performed in shielded rooms for radiated emission or susceptibility testing is notoriously poor (5,6). In fact, the uncertainty encountered in radiated measurements needs to be addressed and more clearly understood (7).

The final immunity test of any electronic device, equipment, or system to the EM environment is a well-planned verification of operation in the actual operational environment. To this end, whole-system testing methods are needed that can simulate operational environments. Today, the primary whole-system testing employed is a victim-source test wherein a systematic check is made to see if on-board transmitters will disrupt the operation of other electronic equipment (5); this method was developed for aerospace vehicles.

4. Other Problem Areas

Many electronic systems fail due to the lack of EMI consciousness among the people who work on the system--designers, manufacturers, operators, and maintenance staff. For example, many specifications are developed by people who do not understand the EMI problem and have no awareness of the EMI measurement problems. There are few, if any, maintenance facilities for military hardware that test for EMI acceptance prior to returning the part to the parent vehicle; this is probably due to a lack of EM1 consciousness and measurement methods.

A complete evaluation of immunity and emission for electronic systems and components to blanket specifications is very time consuming and expensive. Adequate automation of such measurement methods is lacking. Where EM environmental conditions are known, tailored specifications for EMI measurements would be more economical.

The NBS EMI Measurement Program

The electromagnetic interference problem first became significant during World War II; however, due to the lack of a scientific understanding of the phenomena and a lack of tools (such as computers) needed to address the problem, only empirical solutions could be undertaken in developing testing methods, which lead to very large error bounds in these methods. This situation necessitated the overdesign of EM hardening measures in critical applications to assure acceptable performance of electronic devices and equipment. With the advent of the transistor and the integrated circuit, these large error bounds in testing were impossible to handle in design and performance testing; therefore, a new emphasis on EM1 measurements was needed. In fact, the new semiconductor technology made available superior computer systems that offered us new capabilities with which to address these complex problems.

The National Bureau of Standards has an EMI program with the goal to develop a metrology base by which the EMI problems can be understood and attacked. The approach is analytical in nature and begins with the inception of an idea or concept which is then investigated to establish a sound theoretical foundation after which its experimental feasibility is established. If, at this point, the results are favorable, a project is established by which practicability is demonstrated and the results disseminated.

1. Measurements of the EM Environment

The thrust of the NBS program directed toward measuring the EM environment is aimed at developing approaches that will assess the near-field, or near-field like, environment. If this problem can be solved, then it is immediately applicable to intermediate and far-field environments. Accordingly, the first challenge addressed in 1969 was to measure the leakage radiation from the microwave oven. The design chosen for a radiation monitor had three orthogonal dipole antennas in an isotropic arrangement with diodes at the center of each dipole. This design resulted in a very corn-. plicated and expensive unit that was used in the initial microwave oven evaluations as well as in other bioeffects and environmental evaluations (8). This instrument only measured the total electric field at a point in space. Further development of this work included an isotropic antenna system with a fiber optic link used to convey amplitude and frequency information (9), although this had a limited frequency response. The frequency response of each of these devices was limited by the antenna response; an antenna that has no resonances was needed. NBS has since developed an antenna that has a limited bandpass with no out-of-band resonances. Figure 5 shows the pass band response of this antenna (10) which is presently being adapted to several environmental measurement systems (11). Further, a more reproducible broadband electric field meter was developed at NBS, figure 6, to measure fields in the 0.2 to 1000 MHz frequency range from 1 to 1000 V/m(12). An instrument based on this design is now being marketed commercially.

Antenna research to devise antennas that are more suitable to EMI needs has produced resistively-loaded horn designs (13) that have a broadband character together with reasonable directivity. Current antenna research is developing an antenna design that can measure electric and magnetic fields simultaneously (14) and should be adaptable to near-field environmental measurements; such an antenna will be critical to researchers who wish to study near-field interference phenomena in both electronic and biological systems. Other research in progress is pursuing a method of getting amplitude, frequency, and phase information with a large range of frequency response from the antenna to the receiver by a fiber optic link (15).

2. Generation of EM Environments

There is a need for generating well defined EM environments that can be used for evaluating newly developed antenna designs and probes. Such environments can be useful for evaluating the EMI immunity of newly developed electronic equipment. NBS has developed techniques for generating reference EM fields. These include the TEM (transverse electromagnetic) cell (16), anechoic chamber (17), ground screen open-field site (18), and standard loop calibration system (19). It takes a great deal of effort to evaluate and assess the uncertainties in establishing reference EM fields, so a dipole radiator is being developed that may serve as a tool for more easily evaluating such facilities.

Research is currently underway to investigate methods of generating and evaluating less well defined environments. For example, mode-tuned and mode-stirred chambers are currently being used for EMI immunity testing, but such designs of reverberation chambers are not well characterized. Statistical measures must be developed together with methods to explore field uniformity in such reverberating chambers if they are to produce reliable testing methods; NBS is currently addressing this technical problem.

So far, all these techniques are single-frequency testing methods. In the future, there will be needs to develop multiple-frequency environments and simulation techniques for operational environments.

3. Measurement Methods for Emission and Immunity Testing

NBS has examined the traditional shielded room as applied to emission and immunity testing (6) and has confirmed that modifications to it are necessary if it is to be made a useful facility. Judiciously locating anechoic material on the walls of the shielded room can improve its peformance as a testing facility (6). However, a shielded room can be modified into a form of transmission line cell and its performance comparably improved (20) although its usable volume for testing is compromised and the frequency range for use limited.

A new method for evaluating emission radiation from electronics equipment has been developed from theoretical investigations of the TEM cell (21). This method will determine the radiation characteristics of leakage in both total radiated power and a detailed radiation pattern. While this method is limited by the practical constraints of a TEM cell, it is amenable to automation.

Having pursued the TEM cell for immunity measurement methods (22) for several years, NBS is currently investigating the Use of reverberating chambers. Presently, the method employs a mode-tuned arrangement where a matrix of probes of the EFM-5 design (12) are being used to investigate the uniformity of field structures in the chamber. Later, the effects of the item under test on the field structure will be investigated, and the reliability and repeatability assessed in performing immunity testing. The reverberating chamber approach may offer an effective means for using existing shielded rooms.

The final immunity test of any electronic device, equipment, or system to the EM environment is the verification of normal operation in the actual operational environment. A substitute could be the effective testing of the whole system, but today no adequate means exist for whole system testing (5). Consequently, NBS has begun a theoretical investigation into a novel concept for whole system testing.

4. Future Directions

Three areas that need consideration in planning future measurement efforts at NBS are:

a. The development of statistical methods of analyzing and describing the EM environment. The EM environment has a steady state component and a time varying component that jointly indicate a time varying character to the environment. However, the EM environment also has a spatial varying character in that measurements at specific locations give different results. This nature of the EM environment suggests a need to develop tools for characterizing its properties so that more reliable methods for specifying the environment may be developed.

b. An investigation is needed to understand the physics of why semiconductors fail due to EMI. Such understanding could suggest a change in fabrication or manufacturing methods to increase the immunity of semiconductors to EMI phenomenon.

c. More reliable methods for measuring the shielding effectiveness of materials is necessary to facilitate the assessment of various plastic or composite containers for electronic cases. current methods are relatively crude and inadequate for industrial needs.

Conclusion

The combined effect of the increased uses for semiconductor technology in our technically based society and the increased proliferation of radiating sources are increasing the potential for EMI problems. The challenge is to provide better measurement methods for assessing the EM environment and for evaluating the immunity levels of electronic devices, equipment, and systems. Existing EMI measurement or testing methods are inadequate and new approaches are being developed, but a greater appreciation for improved measurement science in this field is needed.

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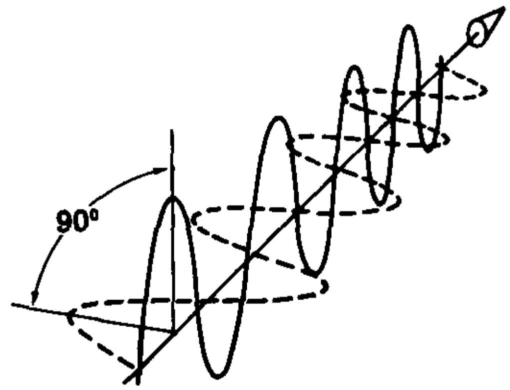

Figure 1. An artist's concept of an electromagnetic wave.

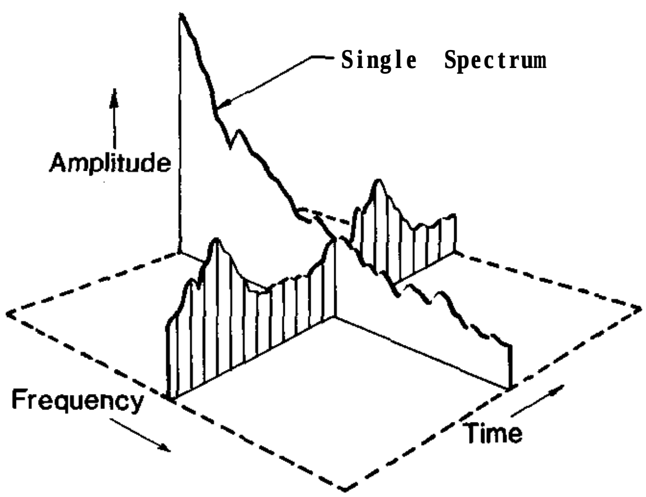

Figure 2. Plot of electromagnetic wave parameters as a function of frequency and time.

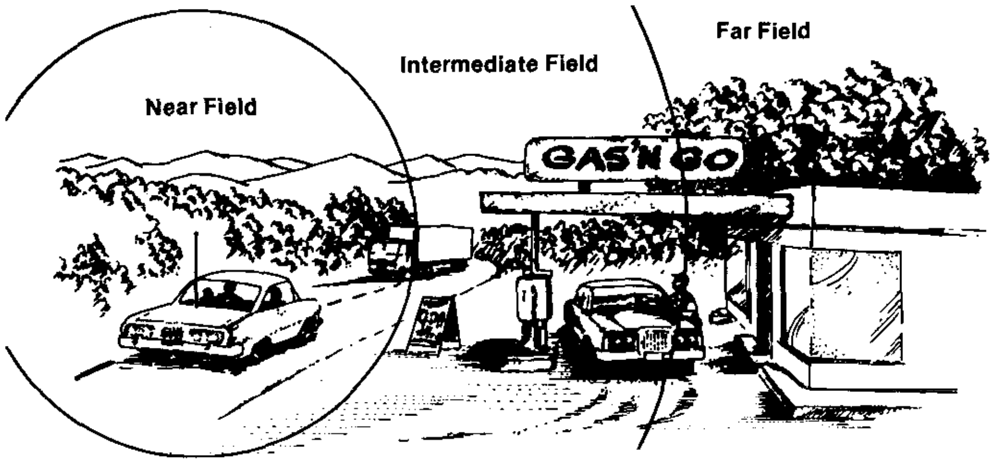

Figure 3. The zone of EM wave typically radiated from an antenna.

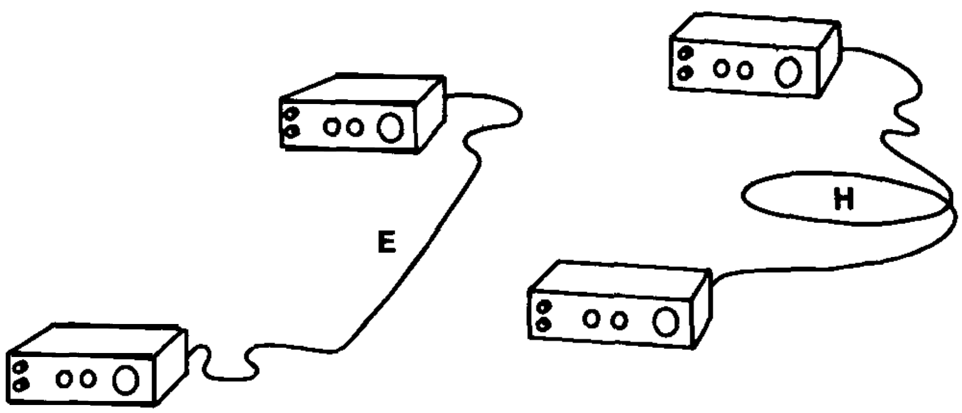

Figure 4. Two electronics packages connected by a wire or cable Illustrating interception of electric and magnetic fields.

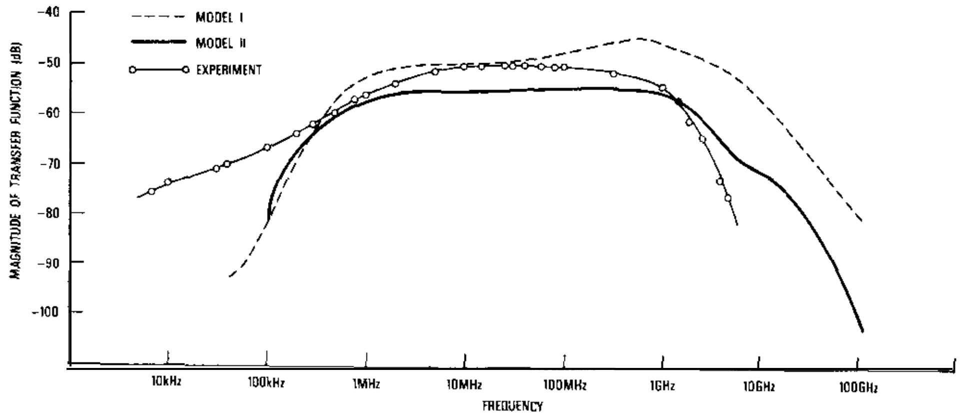

Figure 5. Transfer function of a traveling-wave linear antenna with a nonlinear parallel load.

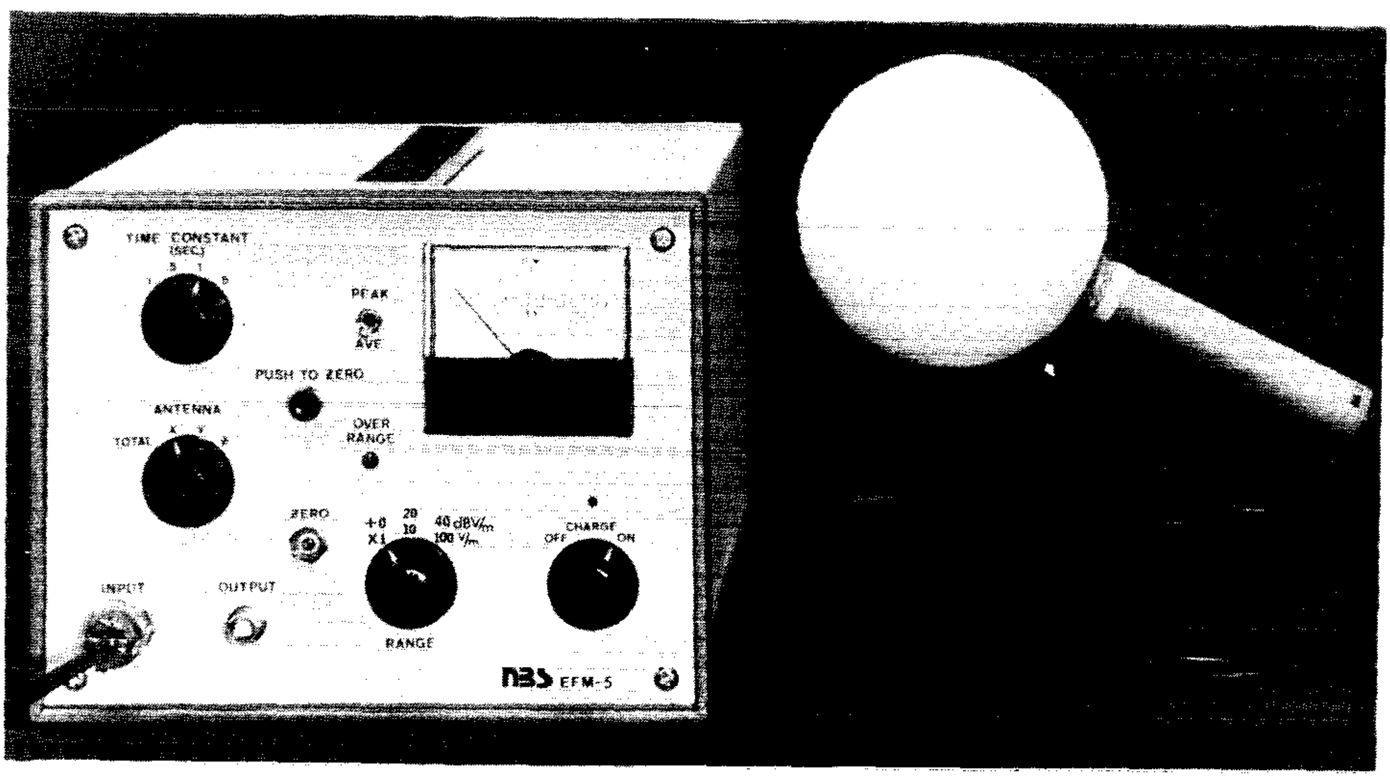

Figure 6. Photograph of the EFM-5 rf radiation monitor.

LASER MEASUREMENTS*

Aaron A. Sanders
Electromagnetic Technology Division
National Bureau of Standards
Boulder, Colorado 80303

INTRODUCTION

Since the discovery of the laser some twenty years ago, applications have proliferated to where their use includes nearly all disciplines of engineering and science as well as medicine, art, information processing, communications, weapons, display effects for rock concerts, and industrial processing. These applications include lasers of various wavelengths from the ultraviolet to the far infrared and encompass CW as well as pulsed lasers varying from very low levels of power, at the limits of detection, to levels of power so high as to include applications of laser weaponry.

For a number of years the Optical Electronic Metrology Group of the National Bureau of Standards has conducted research aimed towards developing national standards and measurement services for critical parameters which characterize lasers. The principal direction of this work is for standards and measurements which promote commerce, trade and the development of science and engineering of lasers and laser applications.

The properties most unique to laser beams, as compared to other forms of optical radiation, are the coherence and spectral purity of the radiation. These two related quantities give rise to other characteristics of interest such as potentially extreme levels of peak power, short pulses, ultra frequency stability, intense beams with divergence caused only by the optics utilized, speckle patterns, its construction, and mode of operation. All these listed properties can vary significantly depending on the particular kind of laser, its construction, and mode of operation. All the parameters may be important for a particular application and in some cases may impose an extreme measurement problem. The emphasis of the work at NBS for standards and measurement techniques appropriate to lasers and laser systems has been to emphasize those generic and specific parameters having a significant or national impact on science, engineering and laser safety, or promotes commerce and trade. These measurements include CW power, pulse energy, pulse duration, peak power of pulse, attenuation, and beam profile.

This talk will review some of the national standards and measurement services for lasers available at NBS, highlight some of the current research, and indicate some of the future needs and direction of NBS laser metrology research.

NBS PROGRAM IN LASER POWER/ENERGY MEASUREMENTS

The approach for laser power/energy standards has been to emphasize standard detectors. This is because they are convenient to "se and no one knows how to construct a laser of known power/energy from fundamental principles. The national standards developed and maintained by NBS are calorimeters. The calorimeters consist of a light trap, equipped with thermal sensors and electrical heaters, which captures and absorbs all the incident optical radiation in the laser beam. The entire mechanism is enclosed by a copper jacket controlled to about 1 milli-degree K. The temperature sensor measures the temperature rise resulting from the absorbed optical radiation. The absolute calibration constant is determined by observing the response for known amounts of electrical energy deposited in the heater attached to the optical cavity. The device then essentially compares the response from optical radiation to the response from known quantitites of electrical energy. The optical cavity can consist of a surface absorber unless the fluence of the laser beam exceeds about 200 ml/cm^2 in times shorter than 1μs. In this case surface absorption can become non-linear and one must absorb the beam within a volume. Studies at NBS and elsewhere have developed suitable volume absorbers for most laser wavelengths and power/energy levels.

The NBS developed calorimeters are designed into measurement systems from which other transfer detectors can be calibrated. These calibrations are performed on a users, instrument or on NBS maintained transfer standards used in a laser measurement assurance program. Table I depicts the range and nominal accuracy of the various measurement systems and Table II lists the established measurement services. Special Test Calibrations can be performed for levels not listed.

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The current research challenge in laser power/energy measurements is for absolute measurements of very low pulse energy (10^{-15} joules) for the spectral range of .4-15 µm, extremely high laser pulse energy (15 kJ for pulses of 1µs or less) for excimer, chemical, iodine, and CO_2 lasers, and peak power measurements for laser pulses of 1-10 picoseconds. These ranges of laser measurements are needed respectively for wavelength agile laser target designator receivers being developed by DoD, DoD High Energy Lasers, the laser safety and picosecond time resolved spectroscopy. NBS has active research programs in each of these areas which is expected to culminate in standards within the next two-years.

BEAM PROFILE

Laser beam profile measurements imply some set of measurements of the laser beam, in a plane near the output of the laser, which permits one to predict the power or energy density of the beam in a plane far removed from the laser (far field). Since, light propagation is specified through Maxwells equations, knowledge of the electromagnetic fields themselves (not the intensity) is required. In fact, complete information consists of a measurement of the amplitude and phase of the electromagnetic field at intervals of about the wavelength of the laser beam radiation. Since no known optical detectors measures the electromagnetic fields directly (rather the square Of the fields), indirect methods must be employed. As a practical matter, sampling intervals much larger than 1λ are sufficient for most applications.

Laser beam profile measurements are important for many applications including laser target designators, rangefinders, laser weapons, free space propagating laser communications, and industrial processing.

No national standards of beam profile measurement currently exist but is an area of NBS research. Interferometric techniques are not often used since many applications involve pulsed lasers with pulses of only a few nanoseconds. Beam wandering in such lasers do not allow long time averages.

A technique often used depends on the Fourier transform relation between the near radiation field and the far field (Franhofner region) and the fact that an ideal lens (mirror) has intensity profile in the focal plan which is the Fourier transform of fields at the entrance pupil of the lens. Such techniques are difficult since focal plane detector arrays may consist of 2500 individual elements and uniformity of response, cross-talk, dynamic range, and spectral response may not be well characterized. These techniques are being studied at NBS as well as a spatial filter technique which separates the beam into a convenient set of modes (depending on the laser and the properties designed into the spatial filter). The advantage of this technique is a much smaller number of elements in the detector array can provide sufficient information to determine the far field.

Even greater research challenges await beam profile standards for High Energy and infared lasers.

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TABLE 1

C-series Calorimeter Measuring System
1mW-2W, .4-1.5μm
Nominal accuracy ≈ 1%

K-series Calorimeter Measuring System
1W-1kW, .4-15 μm
Nominal accuracy ≈ 3%

Q-series Calorimeter Measuring System
1mJ-20J, .4-1.1μm
Nominal accuracy ≈ 1%

BB Calorimeter*
10kJ-7mJ 10.6μm
1kW-200kW
Nominal accuracy ≈ 4%

TABLE 2

Special Calibration		At Cost
Measurement Assurance Program for Laser Power or Energy		
514.5 nm	10mW - 600 mW	$1605/yr.
632.8 nm	1mW	1605
632.8 “m	(1μW, 30μW, 100μW) (Cost is $1000 to participants of 1 mW, 632.8 nm, Laser MAP where the intercomparisons are performed together.)	1605
647.1 nm	10 mW - 200 mW	1605
1.06 μm	10 mW - 1 W	1605
1.06 μm	(Q-switched) 100 mJ - 10	2690
10.6 μm	5 - 5 o w	

*This calorimeter system is now maintained by AGMC, Newark Air Force Station, Ohio.

TRANSIENT FIELD INFRARED VIDEO THERMOGRAPHY AS A PROCEDURE FOR NONDESTRUCTIVE TESTING

C. P. Burger[+] and J. Gryzagoridis[++]

[+]Department of Engineering Science and Mechanics, and Engineering Research Institute
Iowa State University, Ames, IA 50011

[++]Department of Mechanical Engineering
University of Cape Town, South Africa

A feasibility study has been completed which indicates that infrared scanning of transient heat flow has great potential as a technique for nondestructive evaluation of metal components. Analytical predictions have been substantiated by qualitative experimental results.

INTRODUCTION

Radiography and ultrasonics are the two primary techniques used in the nondestructive evaluation (NDE) of flaws in engineering components and structures as well as in the biological field. Whether used separately or together, they do not meet all the requirements of contemporary technology.

Thermographic NDE provides a record of the surface temperature of an object of interest, and from this record information about the internal makeup or structure of the object is revealed.

Based on the advances in infrared detector technology since the 1960s and the quality of real-time infrared thermographic systems, a considerable amount of research has gone into the development of thermal techniques for nondestructive testing. These techniques have been used for a variety of situations in medicine and engineering. In the latter case it has been used on a number of materials ranging from good heat conductors (metals) to insulators (plastics and ceramics) as well as composite materials [1- 9].

In principle, thermographic NDE is simple. Heat is allowed to flow at some point in a test specimen, and the resulting surface temperature distribution provides information about conditions within the object under examination. The choice of the process to generate the thermal field is very wide; it depends on the particular application. For example, transient heat transfer processes are indicated for a number of situations. The process can be initiated on a test specimen by the use of cryogenics, lasers, radiant heat sources, electrical induction, chemical reactions, etc. in any controlled manner chosen by the investigator. On the other hand, steady state heat transfer processes may be indicated and in fact have been employed.

The choice of the surface temperature field detection process is at present fairly narrow. Any surface will emit radiant energy at a rate that is proportional to its absolute temperature to the fourth power and to the surface condition (roughness. color, reflectivity, etc.). Scanning infrared cameras (SIRC) will produce an image of the surface radiation field regardless of whether the field is a result of transient or steady conditions. The use of SIRC may be advantageous in many situations where physical contact with the surface is impossible or undesirable.

Excellent results can also be obtained using cholesteric "liquid" crystals. This is a "contact" type of surface temperature detection and it could be desirable in many situations, both transient or steady state. When a cholesteric crystal is heated it enters a "mesophase" state where it exhibits properties of both liquids and crystals and is capable of scattering white light into its color components, analogous to a rainbow or the color images from an infrared scanning camera.

For the recording and analysis of thermographic images, there are available very advanced still cameras, cinematographic cameras, video tape cassette systems, and a range of hardware and software for digitizing and storing the images.

PROBLEM AREAS

Before any infrared testing can be undertaken the related heat transfer problem must be analyzed. Since infrared scanning techniques are operated in a remote fashion, often considered advantageous, there are some inherent problems as outlined below.

The radiant heat received by the camera is defined as the total amount that leaves the surface viewed by the camera. (Here we assume that the camera sees nothing else.) This is called radiosity (J) and is the sum of the energy emitted and the energy reflected by the surface

$$J = \varepsilon E_b + \rho G \quad (1)$$

The energy emitted from a real surface is given by the expression ε Eb where Eb is the amount of energy that an ideal surface can emit at a given temperature

$$E_b = \sigma T^4 \quad (2)$$

and ε is the total surface emissivity which in turn depends on the quality of the surface σ Is the Stefan-Boltzman constant.

The reflective portion of radiosity (ρG) is indicated by the portion (ρ = reflectivity) of the total Incoming radiation (G) from surrounding sources to the surface.

Unless the emissivity and reflectivity of the surface being tested are uniform throughout the entire area, temperature variations may be observed where In fact they may be nonexistent. Great care should therefore be exercised in interpreting infrared scanned data.

Often atmospheric conditions, CO_2, or water vapor, which absorb and scatter radiation, or other media (perhaps a mirror) in the camera's line of sight, create considerable noise and suppress mild surface gradients.

Infrared cameras display data either in black and white or color images. Small changes in color or greyness are not easily detected by the human eye. Switching to a larger temperature scan corrects this problem, but only at the expense of sensitivity.

In the areas or problems involving transient heat transfer, because of geometry and boundary conditions it is likely that solutions will not exist or be readily available. In such cases finite difference or finite element methods have to be employed. With the present state of technology in digital computers, Intricate geometries and complicated boundary conditions can be accommodated with little effort.

While qualitative results may satisfy certain needs, the shift toward quantitative flaw detection has become quite evident in recent years. As yet no information is available as to how small defects can be detected by a SIRC or cholesteric crystals.

Although sensivivities for infrared equipment are reported to be in the neighborhood of 0.1°C or better and for thermal resolution with liquid crystals as high as 0.007°C, that does not tell how small a defect in a solid can be detected or how deep below the surface it would have to be in order to be detected.

It Is suspected that each particular application must be investigated extensively in order to establish reliable limits of accuracy. Needless to say, the first step is always to establish whether any abnormal temperature distributions exist to suggest the presence of a flaw (qualitative). Subsequently the procedure can be refined to give a quantitative clue to the kind and size of flaw.

FORMULATION AND NUMERICAL SOLUTION OF THE PROBLEM

The system under investigation consists of a three dimensional plate containing a flaw as shown in Fig. 1. It was decided to investigate the surface temperature distribution of such a system subject to unsteady state heat conduction with the following boundary conditions:

The solid has very large dimensions in the x and z coordinates.

The planes $x = 1$, $z = 1$, $z = 13$ are planes of symmetry.

The flaw is always at the midplane and has minimum dimensions of Ax, Δy, Az.

The solid is initially at a uniform temperature (zero degrees).

The two surfaces exposed to the ambient temperature are assumed to be insulated.

The flaw is assured to be made of insulated material: i.e., it does not allow any heat flow through It.

The surface of the solid bounded by $x = 1$, $y = 1$ and all z values is suddenly subjected to and thereafter maintained at a temperature step of 100 degrees.

Utilizing a finite energy balance technique on each volume element the surface temperature distributions as a function of time obtained. The procedure allowed for the positioning of the flaw anywhere In the solid, provided it was always in the $z = 7$ plane. Thus a symmetrical field around the flaw was obtained.

Typical results are shown in Figs. 2 and 3. Figure 2 depicts a three-dimensional representation of the surface temperature distribution for a solid that contains a flaw at nodal point (4,1,7); i.e., on the surface. The flaw has the dimensions Ax = Ay = Az. The temperature distribution shown results, after 28 time intervals have elapsed since the temperature change, in (1,1,z). Figure 3 depicts the solution of the surface temperature distribution for a plate with a "hidden" flaw at (3,2,7) after 28 time intervals have elapsed since the step temperature change at (1,1,z).

The real Impact of both figures is qualitative in that they demonstrate the geometric configuration of the surface temperature plot in the vicinity of the flaw.

The nodal point equations contain the dimensionless parameter M, which is composed of the characteristic dimension of the element Ax, the thermal diffusivity of the material (a property) a, and the time increments from one observation to the other, AT. In a three-dimensional system the choice of the value of M was limited to a minimum value of six. Values less than six generate an impossible condition that violates the second law of thermodynamics. Furthermore, the choice of $M = 6.0$ makes the calculation particularly easy. Once the value of M is chosen and the value of Ax is established, the time increment $\Delta\tau$ is fixed. Having this information and the surface temperature profiles from the example In Table I, which gives typical results, one can obtain a comparison between a flawless and a flawed plate.

Comparison of plates made of different materials is possible. For example one can predict the different times at which steel plates will exhibit the same temperature field near the flaw compared to times for plates made of aluminum, plastic, etc, For example, If the plate were made of 0.5% carbon steel 15.4 mm thick and contained a flaw at (3,2,7) it would take approximately 5.7 s for the temperature over the flaw to be 2.6 degrees higher than that of a flawless plate. If the material were aluminum the time would be shortened considerably to 0.9 s because of aluminum's larger thermal diffuslvity, $\alpha(0.33\ m^2/h)$. If the material were plastic (Epon828) the time elapsed would be approximately 9 mln, again because of the very different thermal diffuslvity, $\alpha(5.5 \times 10^{-4}\ m^2/h)$.

Another important fact is revealed when some of the results of the computer analysis are plotted as In Fig. 4. Here we have a selection of results for flaws having the same dimensions as our grid Ax = Ay = Δz and positioned one and two Δy's below the tdp surface and at different Ax's from the point of application of the step temperature change. The obvious Is borne out: one expects larger temperature differences closer to the source of energy; however, as the time increases these surface temperature differences reach a maximum value and then they start decreasing. It is clear that an optimum time/distance combination exists for most effective inspection.

It Is also apparent that the magnitude of surface disturbance that is produced directly above the position of a defect depends on Its depth from the surface as well as the distance from the position of the step temperature input. To overcome this difficulty, it might be sufficient to move the step temperature input systematically until the entire surface is scanned. Another way would be to impose a larger step temperature.

The first tests performed employed an aluminum plate 152 x 76 x 19 mm which "as drilled wlth a 3.2 mm drill to approximately 1.6 mm below the top surface at distances of 12.5 mm, 50 mm, and 87.5 mm from the edge along the length of the center line. These holes represented hidden "flaws." Thermocouples were placed directly above these "flaws", and another set of thermocouples "as placed parallel to and approximately 1/2 in. away from them. The corresponding thermocouples were connected in a differential mode and their output "as recorded on a chart recorder. Figure 5 represents typical results when the plate's edge "as subjected to a step temperature change by exposing It to boiling water. Attention is drawn to the similarity of these curves to those predicted by the numerical solution and shown in Fig. 4. Again, the importance of optimizing the distance between flaw and heat input is clear.

With the magnitude of temperature differences recorded by the thermocouples being well within the sensitivities of Infrared equipment, the authors proceeded with the following tests. Using an AGA Thermovision model 661 a number of tests were performed with the aluminum plate as well as a steel plate. Subsequently these plates were modified and mounted in a rig where they could be heated and the behavior of both observed simultaneously. Separate tests were performed on pieces of plastic (Plexiglas).

Tests were also performed on the metal surfaces (steel and aluminum plates) using the same heating technique but employing liquid crystals In order to observe their behavior. The liquid crystals were applied by a) placing in direct contact with the metal surface a thin plastic film containing 1°C sensitivity cholesteric crystals which activated at 40°C, and b) by applying directly on the metal surface a layer of 2°C sensitivity cholesteric crystals which activated at 30°C.

A summary of observations resulting from this study, which at this stage can be termed an exploratory or feasibility study, will serve our aim of sharing our experiences with other researchers.

A transient heat transfer field will produce a disturbance on the surface temperature field of a "flawed" plate as predicted by the numerical solution and observed on the thermograms. Isotherms will bulge when approaching the flaw and recede when leaving It. This "as observed particularly when using the liquid crystals as a detector.

The time dependence of the magnitude of the disturbance over a flaw was observed to behave as predicted by the numerical solution. That is, the temperature differences near the flaw increase with time, reach a maximum, and subsequently decrease. This is strictly a function of the thermal diffusivity of the material. This was quite evident when the steel and aluminum plates were tested simultaneously. By the time a distinct pattern "as established In the steel plate behavior, the behavior on the aluminum plate had undergone Its maximum or more distinct pattern.

Of course similar patterns could not be observed with the liquid crystals used because of their very narrow activation range. Instead of a pattern, an isotherm "as observed moving on the surface of the plate. The ideal combination for cholesteric crystals is a very large temperature activation range with the smallest sensitivity compatible with the activation range.

The numerical solution predicted that the position of the flaw relative to the point of heat Input would have an effect on the magnitude of the disturbance of the thermal field. The thermocouple results showed this to be true and also showed the effect of time on the disturbance. The thermograms again corroborated these findings. The nature of the cholesteric crystals precludes this observation when they are used.

In conclusion, the goal of a reliable and viable NOE technique utilizing infrared scanning equipment looks promising.

ACKNOWLEOGHENT

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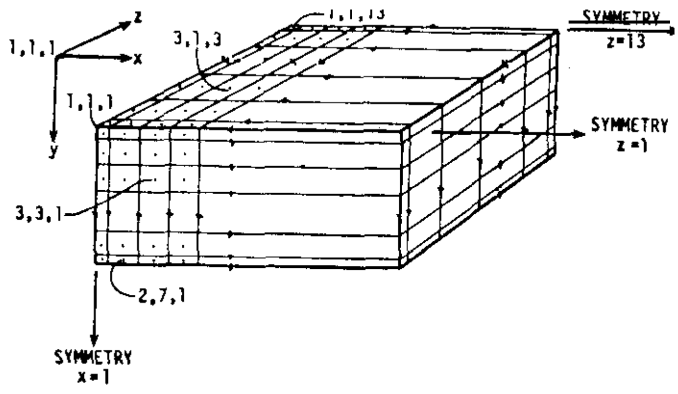

Figure 1

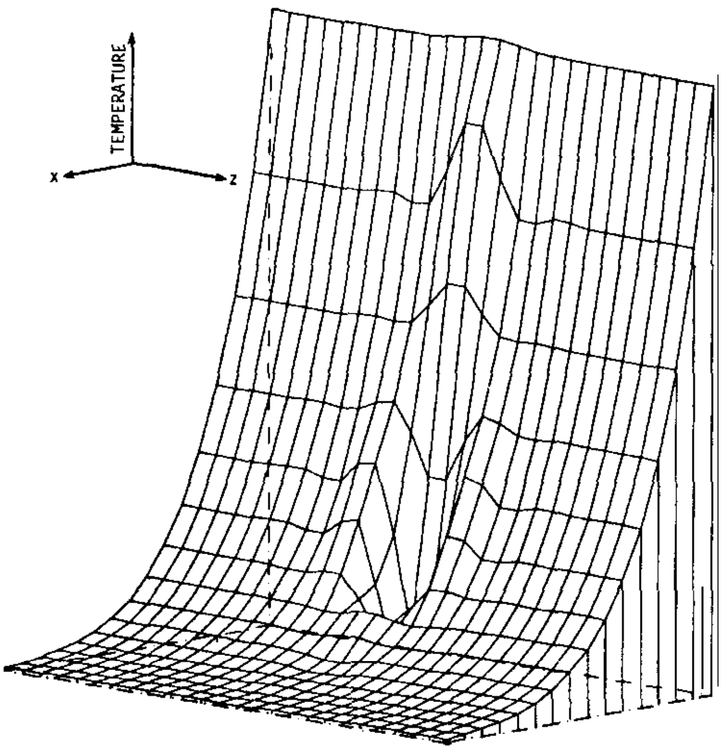

Fig. 2. 3-D representation of the effect of a surface defect on the transient temperature profile.

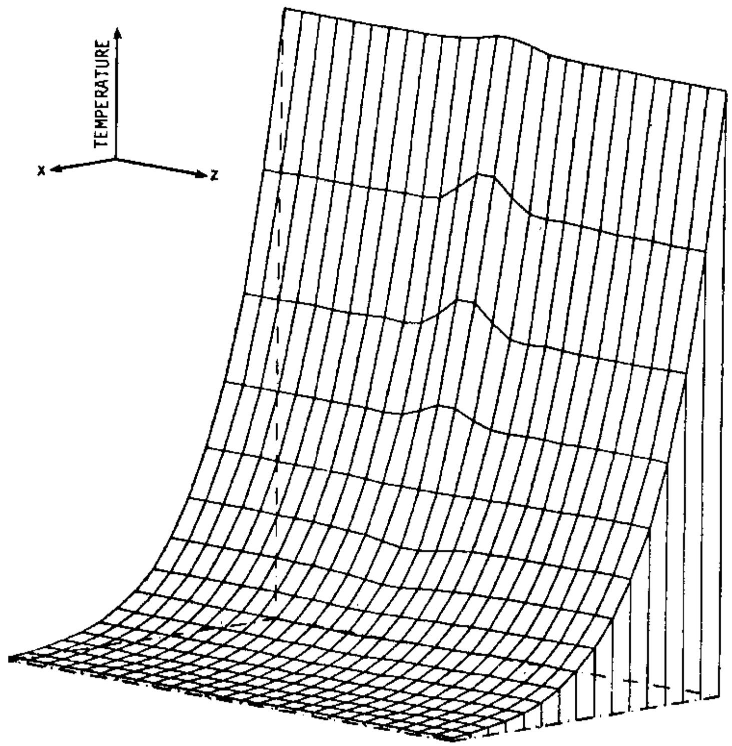

Fig. 3 3-D representation of the effect of a subsurface defect on the transient temperature profile.

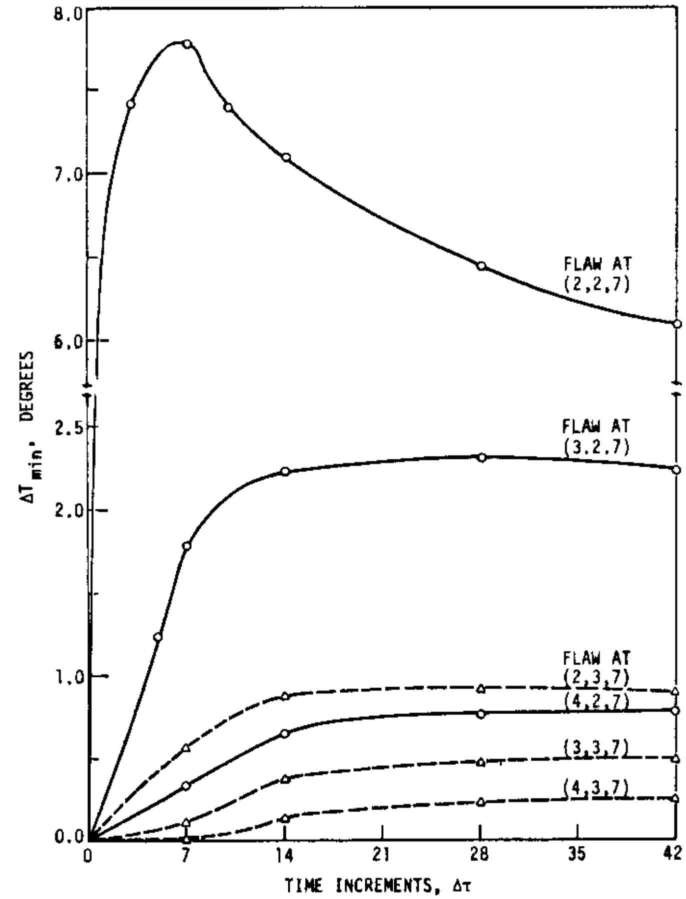

Fig. 4 Step temperature change of 100° at (1,1,z).

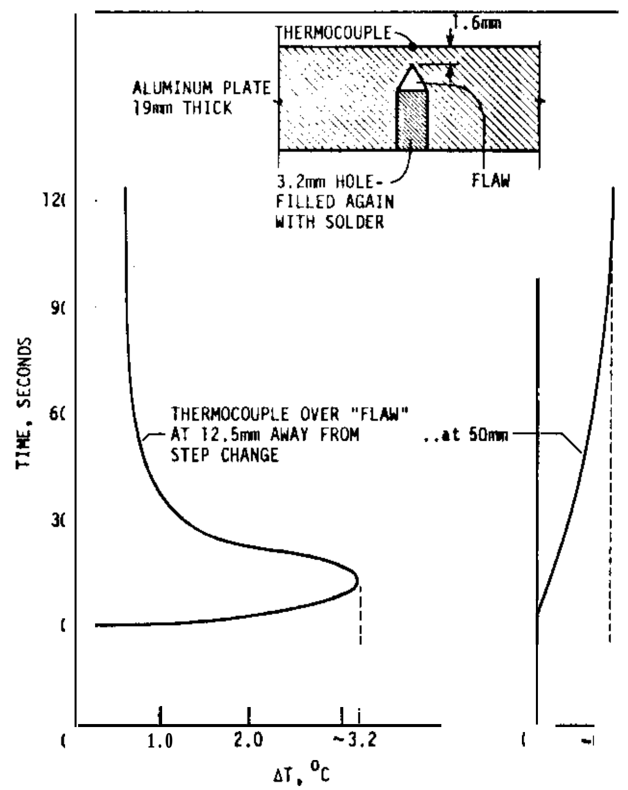

Fig. 5. Thermocouple response with time after step temperature change.

ULTRA-STABLE TEMPERATURE MONITORING AND CONTROL SYSTEMS

Mark F. Smith and Roger M. Hart
Hart Scientific
Provo, Utah

ABSTRACT

Most of the electronic temperature monitoring and control systems that are being manufactured have a problem with stability. A DC system has three main contributors to the stability problem. They are thermocouple effects, input offset voltage drift of the input amplifier, and temperature coefficient of the components. The DC system stability problem can be reduced by using higher quality parts and good engineering practices. Ultra-stable temperature monitoring and control systems can be made by using an AC system which greatly reduces the thermocouple effects. Stability can also be increased by using the proper sensor. A good stable sensor is the platinum RTD.

INTRODUCTION

The technology of electronic temperature monitoring and control systems has advanced rapidly in the last ten years. As technology advances accuracy and stability of temperature monitoring and control systems have improved. Today there are electronic or digital thermometers that are more accurate than the bulb type thermometer. Most temperature monitoring and control systems that are manufactured today are less stable than the bulb type thermometer.

The purpose of this paper is to explain the problem of stability and to show that ultra stable and highly accurate temperature monitoring and control systems can be designed by using good engineering practices. The first section of the paper discusses the problem of stability. The problem of stability is divided into two parts the sensor and the electronics. The second section shows how the problem of stability oan be solved. Finally the last section will deal with applications of the solution.

DEFINITION OF THE PROBLEM

As the need for higher accuracies and stability increases in temperarure monitoring and control, engineers are finding it difficult designing stable and accurate temperature monitoring and control systems. one Of the largest problems in temperature measurement and control is stability and accuracy. Stability refers to the drift of the output of electronic temperature monitoring and control system with respect to time. Drift can be caused by changes in ambient temperature or by component aging. Accuracy is the output deviation from the absolute temperature that is being measured.

There are two main parts in a temperature monitoring and control system that contribute to the stability problem. They are the sensor and the electronics.

Most temperature sensors in electronic temperature monitoring and control systems, are platinum (resistive temperature dector) RTDs, thermocouples, and thermistors. There are two main problems that relate to the stability problem. They are the aging of the sensor and the output sensitivity. For a platinum RTD, aging is very small if the sensor is stress free, and sensitivity is low with approximately 10 to 1 mV/C. Thermocouples have poor aging characteristics and very low sensitivity with approximately 75 to 10 uV/C. Thermistor aging is fair and sensitivity is high with approximately 40 to 10 mV/C. For a highly accurate and stable temperature sensor with a wide temperature range, a platinum RTD is a good choice.

Almost all electronic temperature monitoring and control systems that are presently being marketed are direct current (DC) systems. DC systems use a DC voltage excitation for the bridge circuit (see figure 1). In a DC system the output voltage is proportional to the resistance change of the sensor. The major problems with a DC system is stability. There are three major contributors to instability.

The first contributor is thermocouple effects. Thermoelectric voltages are generated at solder connections and in connectors. Thermocouple effects oan be the most serious contributor to the stability problem. Thermoelectric voltages in a standard bridge arrangement (figure 1) are approximately 50 uv/C. Assuming the sensor output is 2.5 ❑ V/C the over all effect of thermocouples are 0.02 c/c.

The second contribution to instability is input offset voltage drift of the input amplifier. Host common operational amplifiers have offset voltage drift of 10 to 2 uv/C. There are some special operational amplifiers that have Input offset voltage drifts of less than 1 uv/C but they are expensive. With the common operational amplifier and 2.5 mV/C sensor sensitivity, effects of the offset voltage drifts are approximately 0.004 to 0.001 c/c.

The third contribution to instability is the temperature coefficient of components used In the electronics. The largest contribution of component temperature coefficient are the resistors used in the bridge (figure 1). If 100 PPM/C resistors are used in the bridge, the contribution to instability is 0.025 C/C. Gain resistors contribute approximately 0.01 C/C if 100 PPM/C resistors are used.

If all the effects of Instability are added up, the total stability of the system is 0.06 C/C. In a normal room where the ambient temperature change is ±2 C, the stability of the electronics Is ± 0.12. The accuracy cannot be any better than the stability.

SOLUTION TO THE PROBLEM

Stability is a major problem with most DC temperature monitoring and control systems. "he" stability Is improved, accuracy can also be improved. There are two methods to solve the stability problem. The first Is improving the DC system, and the second Is using an AC system.

The first method of improving the stability of a temperature monitoring and control system Is improving the DC system. Thermocouple effects can be reduced by locating the sensitive connections close to each other and use a low thermoelectric voltage solder. This modification can reduce the thermoelectric effect by a factor of two. Reducing input offset voltage is simple but more expensive. When low temperature coefficient components are used In the bridge a large contribution to the stability problem can be solved. By making the necessary modification, stability of a DC system can be improved to 0.015 C/C, which Is an improvement of about four times. But, there are still problems with thermocouple effects especially when different alloys of metal are used In connections. Thermocouples contribute approximately 60 percent of the instability.

Temperature monitoring and control systems can be made more stable than a DC system by using an alternating current (AC) system. An AC system uses an AC voltage excitation for the bridge. After the bridge output Is linearized it is rectified to a DC signal (see figure 2). AC systems have similar problems as the DC system except the thermocouple effects are greatly reduced to less than 0.0003 C/C and these thermoelectric voltages occur after the AC signal Is rectified. When low temperature coefficient resistors are used In the AC system, stability is reduced to less than 0.005 c/c. If very low temperature coefficient parts are used, a stability of better than 0.002 C/C can be achieved. This low stability Is a factor of approximately 30 times better than commercially availble electronic temperature monitoring and control systems.

There are some of draw backs with the AC system. They cost more, use higher precision parts, and more parts. To achieve a highly stable electronic temperature monitoring and control system, an AC system should be used.

APPLICATION OF THE SOLUTION

By using these good engineering practices, Hart Scientific has designed two ultra-stable temperature monitoring systems and a control system.

One of the temperature monitoring systems is an ultra-stable and highly accurate digital thermometer. The Micro-Therm 1006 has a guaranteed system accuracy of ±0.03 C and a typical accuracy of ±0.01 C. The stability of the system is better than 0.010 C/year.

The other temperature monitoring system is an ultra-stable OEM RTD monitoring system. The model 1010 temperature monitor uses a platinum RTD. Absolute accuracy is adjustable to within 0.005 C of an absolute reference. Stability Is typically ±0.005 C/month.

Ultra-stable constant temperature bath, circulator and temperature controllers have been developed that have short and long term stability Of ~0.0005 c. The stability Is rated with 27 liters of water at a temperature range of 10 to 80 C. Other baths with different temperature ranges and stability of less than ~0.005 C depending on the fluid and temperature have been developed.

CONCLUSION

As the need for electronic temperature monitoring and control systems increases, so does the accuracy and stability specification. After reviewing the present manufactured temperatured monitoring and control systems, very few manufacturers make an ultra-stable system. The reason for poor stability is the DC system. By incorprating an AC system, ultra-stable systems can be manufactured.

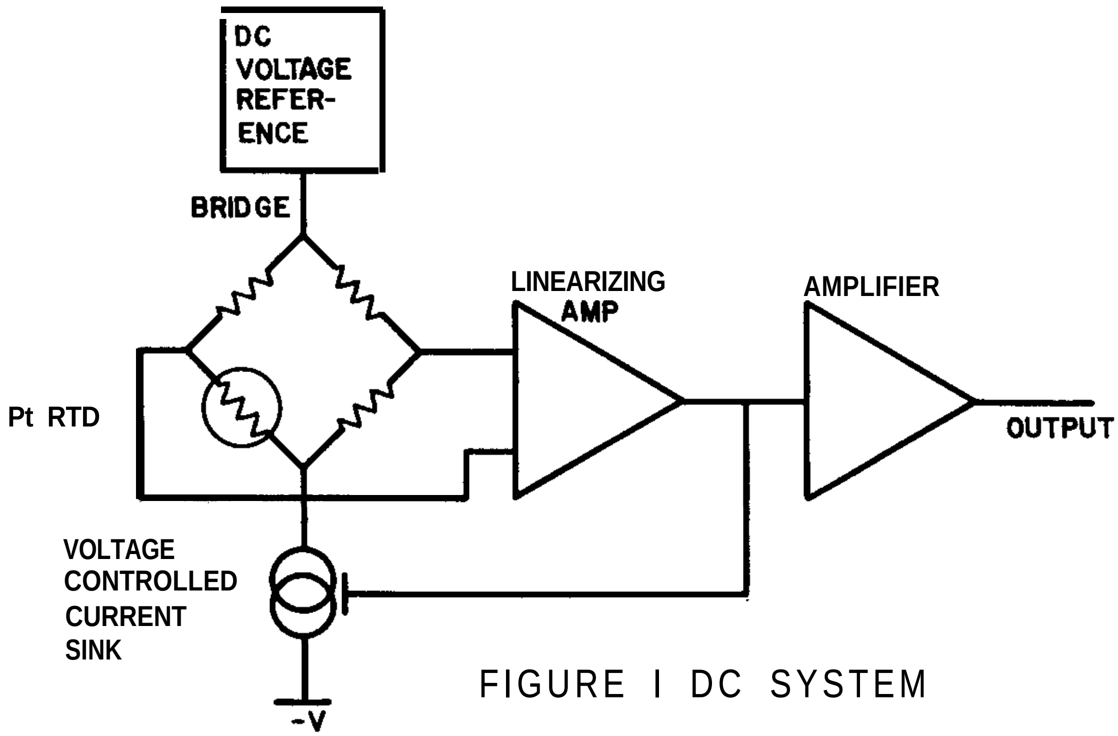

FIGURE I DC SYSTEM

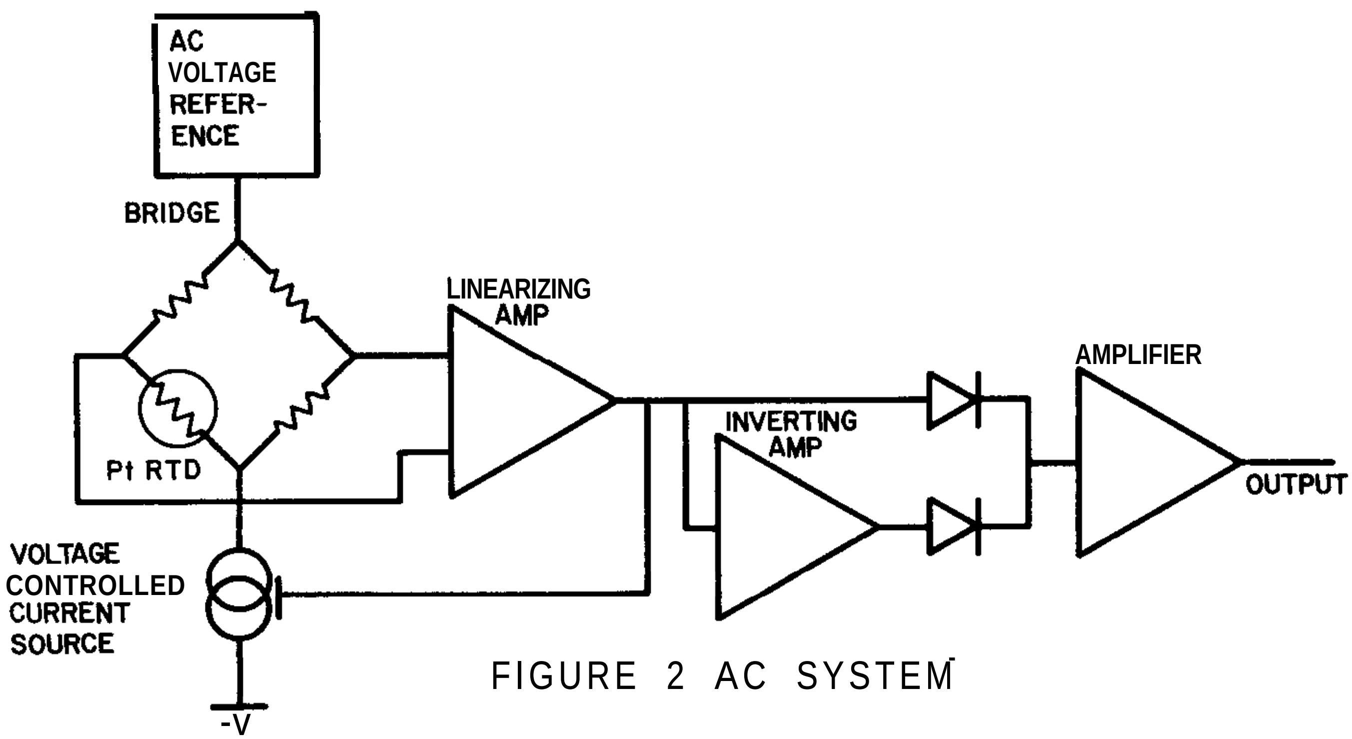

FIGURE 2 AC SYSTEM

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There are two main parts in a temperature monitoring and control system that contribute to the stability problem. They are the sensor and the electronics.

Most temperature sensors in electronic temperature monitoring and control systems, are platinum (resistive temperature dector) RTDs, thermocouples, and thermistors. There are two main problems that relate to the stability problem. They are the aging of the sensor and the output sensitivity. For a Platinum RTD, aging is very small if the sensor is stress free, and sensitivity is low with approximately 10 to 1 mV/C. Thermocouples have poor aging characteristics and very low sensitivity with approximately 75 to 10 uV/C. Thermistor aging is fair and sensitivity is high with approximately 40 to 10 mV/C. For a highly accurate and stable temperature sensor with a wide temperature range, a platinum RTD is a good choice.

Almost all electronic temperature monitoring and control systems that are presently being marketed are direct current (DC) systems. DC systems use a DC voltage excitation for the bridge circuit (see figure 1). I" a DC system the output voltage is proportional to the resistance change of the sensor. The major problems with a DC system is stability. There are three major contributors to instability.

The first contributor is thermocouple effects. Thermoelectric voltages are generated at solder connections and in connectors. Thermocouple effects can be the most serious contributor to the stability problem. Thermoelectric voltages in a standard bridge arrangement (figure 1) are approximately 50 uv/C. Assuming the sensor output is 2.5 mV/C the over all effect of thermocouples are 0.02 c/c.

The second contribution to instability is input offset voltage drift of the input amplifier. Host common operational amplifiers have offset voltage drift of 10 to 2 "v/C. There are some special operational amplifiers that have input offset voltage drifts of less than 1 uv/C but they are expensive. With the common operational amplifier and 2.5 mV/C sensor sensitivity, effects of the offset voltage drifts are approximately 0.004 to 0.001 c/c.

The third contribution to instability is the temperature coefficient of components used in the electronics. The largest contribution of component temperature coefficient are the resistors used in the bridge (figure 1). If 100 PPM/C resist&s are used in the bridge, the contribution to instability is 0.025 C/C. Gain resistors contribute approximately 0.01 C/C if 100 PPM/C resistors are used.

If all the effects of instability are added up, the total stability of the system is 0.06 C/C. In a normal room where the ambient temperature change is ±2 C, the stability of the electronics is ± 0.12. The accuracy cannot be any better than the stability.

SOLUTION TO THE PROBLEM

Stability is a major problem with most DC temperature monitoring and control systems. When stability is improved, accuracy can also be improved. There are two methods to solve the stability problem. The first is improving the DC system, and the second is using an AC system.

The first method of improving the stability of a temperature monitoring and control system is improving the DC system. Thermocouple effects can be reduced by locating the sensitive connections close to each other and use a low thermoelectric voltage solder. This modification can reduce the thermoelectric effect by a factor of two. Reducing input offset voltage is simple but more expensive. When low temperature coefficient components are used in the bridge a large contribution to the stability problem can be solved. By making the necessary modification, stability of a DC system can be improved to 0.015 C/C, which is a" improvement of about four times, But, there are still problems with thermocouple effects especially when different alloys of metal are used in connections. Thermocouples contribute approximately 60 percent of the instability.

Temperature monitoring and control systems can be made more stable than a DC system by using an alternating current (AC) system. An AC system uses an AC voltage excitation for the bridge. After the bridge output is linearized it is rectified to a DC signal (see figure 2). AC systems have similar problems as the DC system except the thermocouple effects are greatly reduced to less than 0.0003 C/C and these thermoelectric voltages occur after the AC signal is rectified. When low temperature coefficient resistors are used in the AC system, stability is reduced to less than 0.005 c/c. If very low temperature coefficient parts are used, a stability of better than 0.002 C/C can be achieved. This low stability is a factor of approximately 30 times better than commercially availble electronic temperature monitoring and control systems.

There are some of draw backs with the AC system. They cost more, use higher precision parts, and more parts. To achieve a highly stable electronic temperature monitoring and control system, an AC system should be used.

APPLICATION OF THE SOLUTION

By "sing these good engineering practices, Hart Scientific has designed two ultra-stable temperature monitoring systems and a control system.

One of the temperature monitoring systems is an ultra-stable and highly accurate digital thermometer. The Micro-Therm 1006 has a guaranteed system accuracy of 9.03 C and a typical accuracy Of ±0.01 c. The stability of the system is better than 0.010 C/year.

The other temperature monitoring system is an ultra-stable OEM ATD monitoring system. The model 1010 temperature monitor uses a platinum RTD. Absolute accuracy is adjustable to within 0.005 C of an absolute reference. Stability is typically ±0.005 C/month.

Ultra-stable constant temperature bath, circulator and temperature controllers have been developed that have short and long term stability Of ±0.0005 c. The stability is rated with 27 liters of water at a temperature range of 10 to 80 C. Other baths with different temperature ranges and stability of less than ±0.005 C depending on the fluid and temperature have been developed.

CONCLUSION

As the need for electronic temperature monitoring and control systems increases, so does the accuracy and stability specification. After reviewing the present manufactured temperatured monitoring and control systems, very few manufacturers make an ultra-stable system. The reason for poor stability is the DC system. By incorprating an AC system, ultra-stable systems can be manufactured.

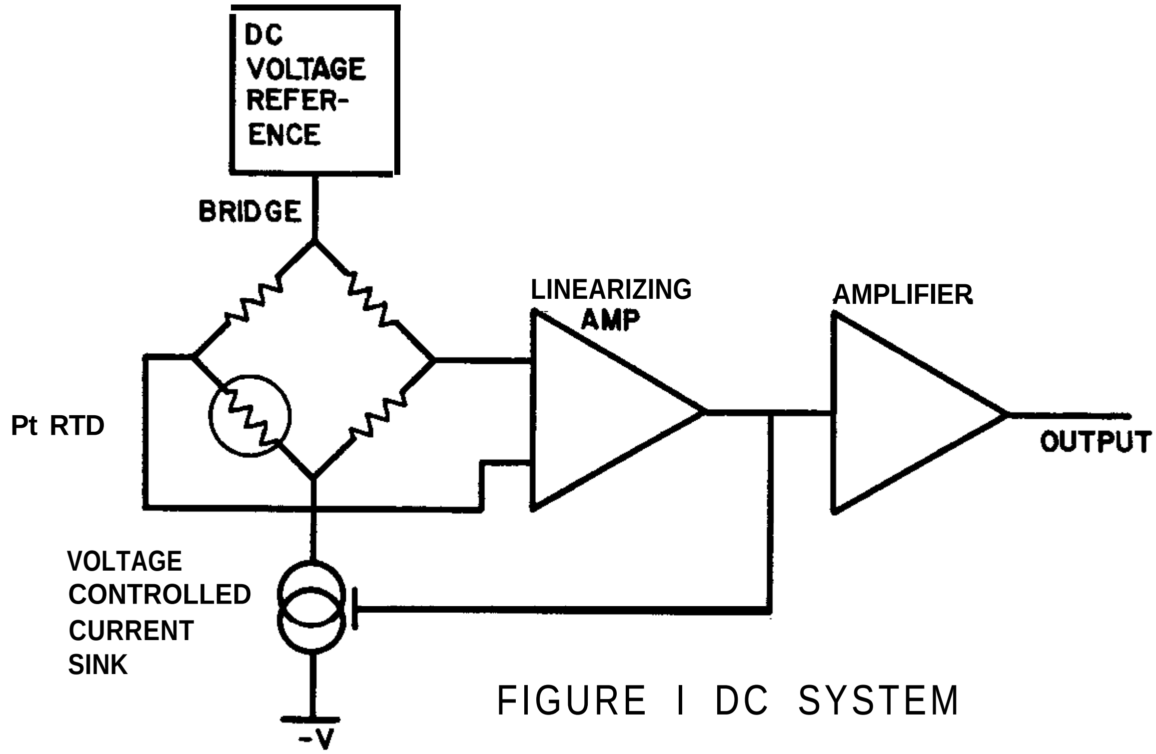


FIGURE I DC SYSTEM

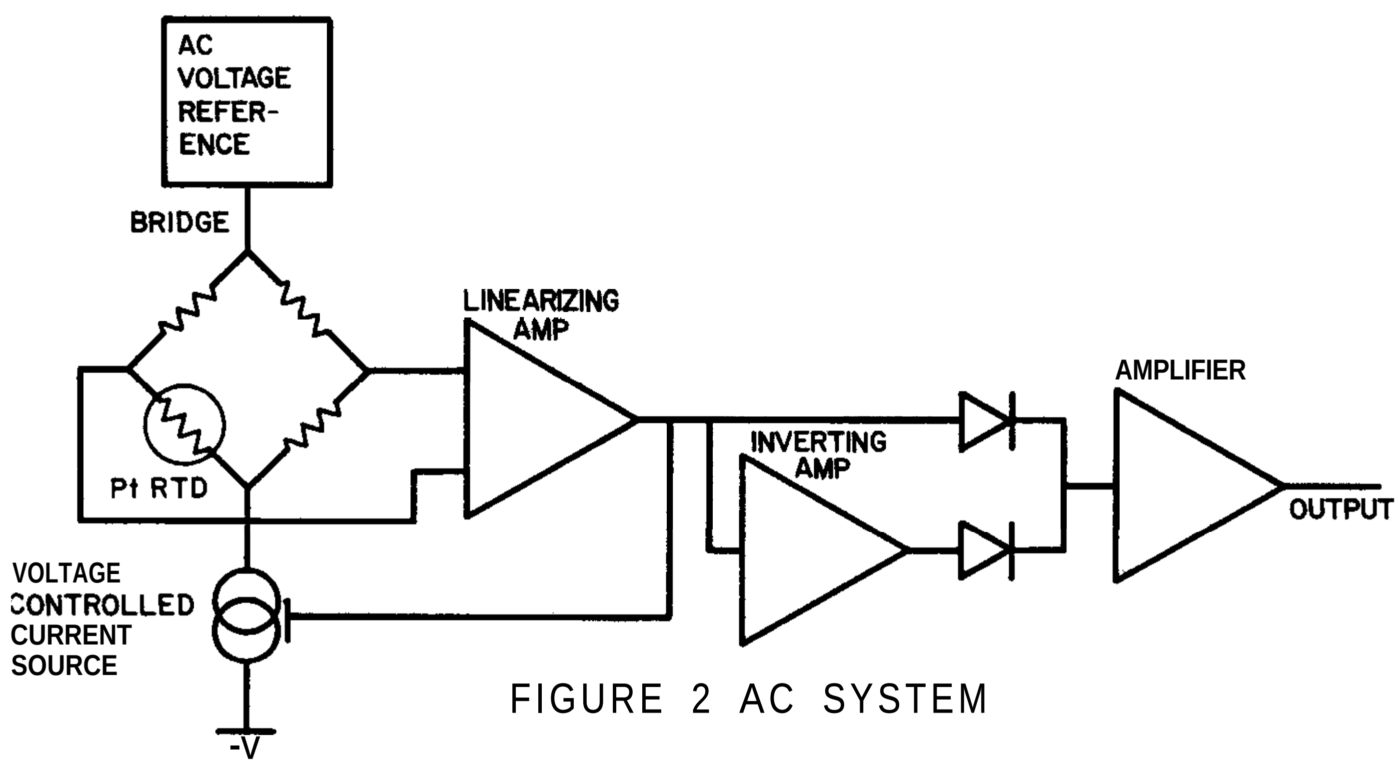


FIGURE 2 AC SYSTEM

HIGH SPEED, ACCURATE MEASUREMENTS ON THE SHOP FLOOR

RUSSELL S. SHELTON
PRODUCT MANAGER
COORDINATE MEASURING MACHINES
E. LEITZ, INC.
ROCKLEIGH, N. J. 07647

INTRODUCTION:

Any attempt to look into the future is risky, as anyone who has ever played the stock market can verify. Still, there are times when we must try. A case in point is the "factory of the future", so called because it will be a combination of existing capabilities together with others yet to be developed. In general terms it will maximize productivity and minimize labor and scrap in order to generate the greatest profit for the manufacturer.

So far most of the effort which has gone into the FOF concept, at least if one can believe what has been reported on the subject, is in the areas of CAD/CAM, robotics, flexible manufacturing centers, etc. Admittedly, some lip service has been given to inspection and quality control, but not too much. This is reminiscent of the 1950's. Remember? NC machine cools had just been introduced, and management fell in love with them. It was only later, in some cases <u>much</u> later, that the need for an equivalent increase in inspection technology became apparent. The purpose of this paper is to identify some of the quality problems which will exist in the FOF, and to offer some solutions.

PHILOSOPHY:

There is a technique of logic called "reductio ad absurdum". This is a means by which you can determine the truth, or trend, of something by decreasing it to its simplest possible terms. Let's do that with the FOF concept:

(1) No manager <u>wants</u> to inspect anything: All he wants to do is make money by making parts.

(2) Labor is expensive and unpredictable. The FOF should eliminate labor.

(3) The U.S. is moving away from the "throwaway" concept. Thus, manufactured parts have to be more reliable.

(4) Tolerances are being tightened to ensure reliability and longer life.

(5) Scrap must be eliminated.

(6) Machine cycle times must be reduced

(7) Inspection must become an integral part of manufacturing.

(8) Inspection results must be looped back to machine tools to correct for deviations.

(9) The environment on the shop floor will remain as bad in the future as it is now.

Clearly, some of the above statements are not totally true, but from the viewpoint of establishing the trends for the future, let us assume that they are <u>substantially</u> correct.

Assuming the philosophy we have adopted to be valid, how do we now fit the Quality Control function into the FOF concept? Broadly stated, we have to have a system which will make highly accurate, rapid measurements under adverse conditions and have the capability of looping the inspection results back to the manufacturing unit within the cycle time of one part, if possible. All of the above features must be applicable to a wide variety of machines (milling, drilling, grinding, EDM, etc.), and to an even wider range of part Configurations produced by these machines. Has it been done? <u>No</u>. Can it be done? <u>Yes</u>. Here's how.

TEMPERATURE 6 ITS EFFECTS ON WORKPIECES

We generally describe the change in shape of an object resulting from differences in temperature by assigning to each engineering material a "coefficient of expansion". This is expressed as a change in length per unit length per unit temperature.

("/"/°F) or (MM/MM/°C)

For most people in everyday life this is perfectly acceptable. But for those of us interested in making very accurate dimensional measurements, it should be considered only an approximation.

Temperature is an indication of energy content. At the atomic or sub-atomic level, all materials are in motion. To make it simple, let us "observe" an electron as it whirls in its orbit. If energy is transferred to this electron, its orbit increases in diameter. It pushes its neighbors aside a bit, much like a man in a crowded subway who reaches into his pocket for a handkerchief, and in the act digs his elbow into his neighbor's ribs. The offended party moves away. The "coefficient of expansion" concept assumes that everyone in that subway car reaches for his handkerchief at the same moment, and that all the elbows are the same length, with the result that a predictable number of people are pushed into the next car. In other words, it is assumed that the material in question is homogeneous. Unless we are dealing with a pure element which, by definition, is homogeneous, this assumption is untrue. The types of engineering materials we must deal with are mixtures of various elements, and even small changes in the ratios of these elements will change the coefficient for a specific part. These changes may be small, but they do exist.

A second problem is that of the rate of energy transfer. Workpieces with varying thicknesses will change shape unpredictably, even if their coefficients of expansion are identical. Figure 1 shows the results of a simple test run at Shelton Metrology Laboratory about 15 years ago. Three parts made from the same melt of aluminum were put in a box, one at a time. Hot water was poured into the box. The water temperature was 125°F ± 1°F. The length of each sample was monitored on an LVDT supported on an insulated base, and the change in part length was monitored as a function of time. At any moment these parts appear to be quite different. Thus it is obvious that measurement taken on a workpiece during a time of temperature change will not necessarily reflect the same results as if the same measurements were taken at a stable workpiece temperature.

The message is clear - you cannot make accurate measurements if temperatures are changing, because parts respond to the changes based upon their own configuration. Additionally, it is impossible to predict, with great accuracy, the steady-state change in size of a part from a base temperature to a higher temperature (or the other way around) because the coefficient of expansion value fqr the part material is not really known far the specific part itself.

TEMPERATURE AND ITS EFFECTS ON MEASURING MACRINES

If we consider a measuring machine to be a workpiece - albeit a very complex one- then it is easy to see that the same factors which create the problems mentioned above will have similar adverse effects on the measuring machine itself. Therefore, if we take a standard CMM, place it on the shop floor, and measure a part with it, what we end up with is an unstable measuring system checking an unstable part.

Over the years various efforts have been made to reduce the effects of temperature on CMM's. Some of these are:

- --Installing the entire machine in a temperature controlled room.
- --Building machines out of only one type material to minimize bi-metal effects.
- --Building machines with bi-metal effects to cancel out temperature effects.
- --Making measuring elements (glass scales, etc.) with tha same coefficient of expansion as the workpieces to be measured.
- --Creating air turbulence in the measuring area to minimize thermal gradients.
- --Surrounding measuring areas with air barriers to avoid drafts.

Clearly all the above measures are stopgap attempts to overcome temperature effects by fighting them. Unfortunately, this has never worked in the past, and will not in the future. Figure 2 shows a simple slide mechanism. In a typical CMM three of these slides would be compounded to provide an X,Y,Z measuring envelope. If we consider the first-order error sources in this single slide we will discover that there are six (6) of them. If we now combine these slide movements, there are 18 first-order errors caused by geometric imperfections, a much larger number of second and third order errors, and last but by no means least, the errors caused by imperfections in squareness between the slides. It simply isn't possible to eliminate these errors, whether they are caused by imperfect component parts or by temperature effects. However it is possible to observe them, and through the use of computers mathematically eliminate them. All we need is a reference system without mechanical error, and totally unaffected by temperature.

A NEW, SELF-COMPENSATING COORDINATE MEASURING MACHINE

The secret to making accurate dimensional measurements in an industrial, which is to say, uncontrolled environment, is to have a reference system built into the measuring machine which is unaffected by that environment, and by its own inaccuracies. Figure 3 shows the basic elements of such a system. A pair of pivot mounted, journal-type air bearings support a round shaft. The center of rotation of each bearing defines a point in space. Since two points define a line, these two bearings fix an axis of rotation far the shaft. We cannot directly measure the axis of rotation, so we must measure the surface of the shaft, which does have errors. However, by rotating the shaft, sensing the same point on the shaft 180° apart, we can calculate the location of the axis of rotation by the formula $\frac{A-B}{2}$ As shown in the sketch, a pair of sensors attached rigidly to a machine slide can observe the inaccuracy of slide movement by repeated calculations taken from the axis of the rotating rod which is "parallel" to the slide.

Figure 4 shows two of these reading heads attached to the same slide. With this setup we can observe any yaw of the slide.

To observe roll/pitch, it is necessary to solve the problem of shaft sag. Obviously in horizontal position our shaft will deflect due to gravity. This deflection far any point is given by:

$$Y \frac{WX(L-X)}{24\ EIL} \left(L^2+X(L-X)\right)$$

Where W = Shaft Weight
L = Shaft Length
X = Distance of Y from one bearing
E = Modulus of Elasticity
I = Moment of inertia

The value of E is, like the coefficient of expansion, an approximation for a specific shaft. To eliminate this, we actually measure the deflection at the midpoint for a specific shaft before assembling it into a slide and, knowing Y, solve far EI. Now we can use this actual value in calculating values for Y at any point. We now have an actual centerline of rotation, corrected mathmatically for sag. Any readings taken from the shaft in a vertical orientation can be corrected by the sag value.

$\left(\frac{A-B}{2}\right)$ - SAG = Vertical deviation of slide

This allows us to use a reading head (Fig. 5) with four sensors. Now roll, pitch and yaw of the slide can be observed. The setup would be identical to Fig. 4, except for four sensors in each head rather than only two.

By combining multiple slides into a well designed CMM mechanism it is therefore possible to determine the roll, pitch and yaw of each slide at any point in their travel. But what about squareness? After all, one arc second is about 5 millionths of an inch per inch of travel. In 20" this leads to an error of .0001". It is not rare to see changes in squareness that are on the order of 20 arc seconds due to temperature changes. Over the same 20" of travel this becomes .002", a totally unacceptable amount.

Fig. 6 shows two shafts, each constructed as above, into two mutually perpendicular slides. Details have been omitted for clarity. We will only look at those elements required to illustrate squareness correction. Shaft 1 protrudes slightly beyond its supporting air bearings. Shaft 2 has an air thrust bearing on one end, and the other end terminates in an arm which contains two sensors. It is carried on a slide which moves "parallel" to Shaft 1. To detect any change in angle between the shafts do the following: Move Shaft 2 to the left end of Shaft 1. Rotate Shaft 2 until the sensors straddle the protruding end of Shaft 1. Rotate Shaft 1, as above, and read the output of the sensors. Again, $\frac{A-H}{2}$ is the location of the axis of rotation of Shaft 1. Now move to the other end of Shaft 1 and repeat. Any difference between the readings is the result of an angular change between the shafts. The air thrust bearing prevents any axial pump of Stage 2, which could confuse the results.

A word about the accuracy of this technique. Repeated experiments at Shelton Metrology Laboratory showed the ability to define and axis of rotation within ± 3 millionths under a wide variety of conditions. An air thrust bearing is also accurate to within these values. The sensors used were matched Eddy-current transducers with digital resolutions of 10 millionths (optional 1 millionth), and linearity of 10 millionths over a .005" working range. Although the squareness was never actually performed it is easy to estimate its accuracy. A 10" lever arm would yield two readings about 20" apart. If each reading is uncertain within 6 millionths, the worst case is 12 millionths uncertainty over 20", or a" angular uncertainty of approximately 0.1 arc second. Assuming uncompensated variables to be 10 times this amount, we should be well within 0.1 arc second angular accuracy regardless of the environment!

To determine length measurement errors a thin-wall, accurately ground cylinder is permanently mounted to the table of the CMM. Its height and diameter are known at 68°. By periodically measuring this part (which will rapidly respond to thermal changes) it is possible to calculate scaling factors to apply to all machine readings. (See Fig. 7)

Finally, the workpiece to be inspected. On the table of the CMM is a tank into which the part is placed (by hand or by robot). The tank is filled with a non-corrosive fluid, which is agitated by a pump. Heat from the part will rapidly transfer to the liquid. A thermal sensor in the tank will detect bath temperature changes. As soon as bath temperature stabilizes (or changes less than a fixed amount per ""it time), the sensor commands the tank to drain. Fluid returns to a holding tank, which extracts the heat by cooling coils and returns the liquid to a preset temperature. The part can now be inspected, and the temperature value observed by the sensor will be used as a scaling factor to approximate the coefficient of expansion of the part. While not perfect, this technique does eliminate hot spots in the inspected part caused by machining. Please remember that we are discussing a" in-line inspection procedure, in which the workpiece is removed from the machine tool immediately placed on the CMM. unless it is cooled portions of such a part could be more than 100°F above nominal. Figure 8 shows such a setup schematically.

I" conclusion, it must be admitted that none of this would be practical without the speed and calculating ability of the computer. Nothing presented in this paper is "Blue Sky". All of these capabilities referred to above have existed for a "umber of years. It is even possible to adapt the principles outlined above to a machine tool for "on-machine" inspection. The process would be to machine a part in the normal way, switch to the sensor outputs for the inspection routine to avoid the machine being blinded to its own errors, and inspect the part while still clamped a" the machine table. This is only a" approximation of a" independent inspection, since part temperature and clamping deflections would be present, but it would be far better than simply putting a sensing head in the spindle and probing the part.

The "Factory of the Future" will never reach its full potential unless inspection techniques are rethought so as to be adapted in a practical way to the harsh environment which exists on the shop floor. This paper is intended to show one way in which this can be accomplished.

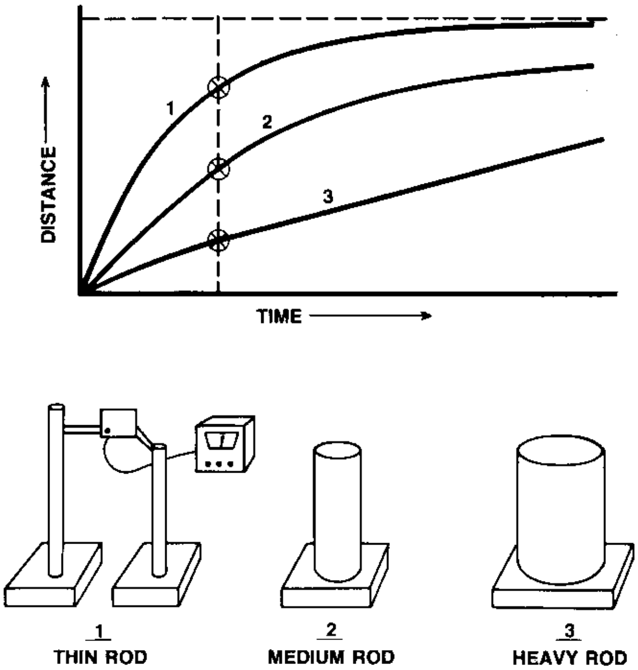


Fig. 1

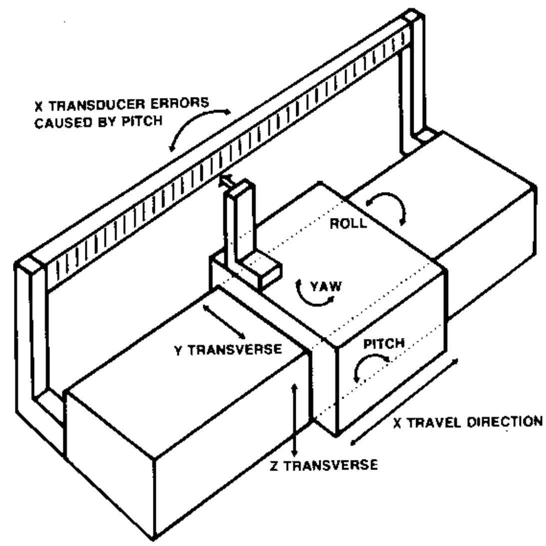


Fig. 2

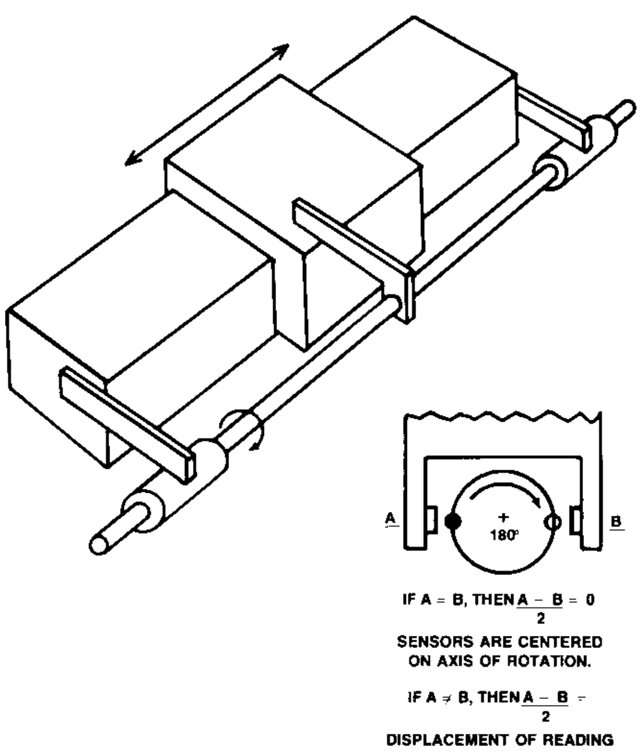


Fig. 3

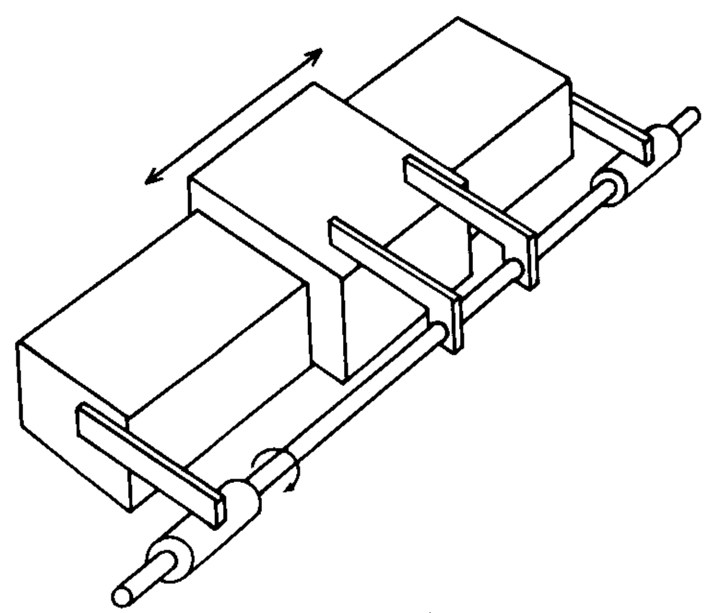


Fig. 4

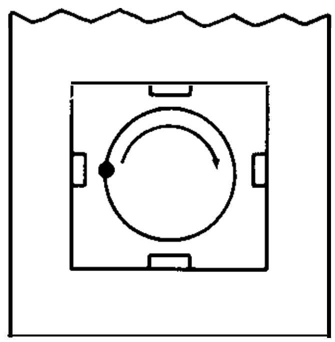


Fig. 5

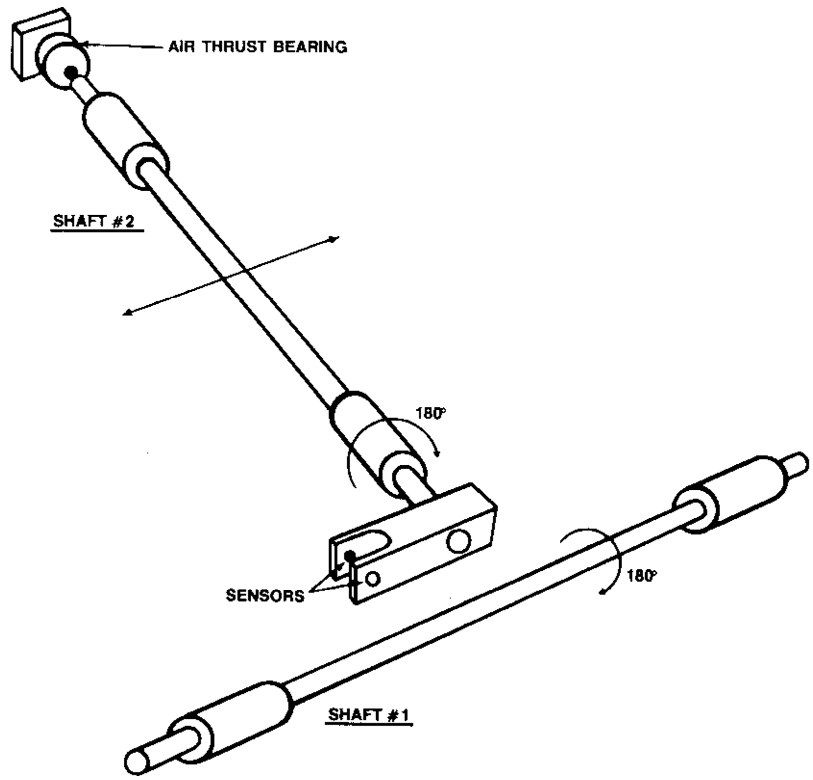
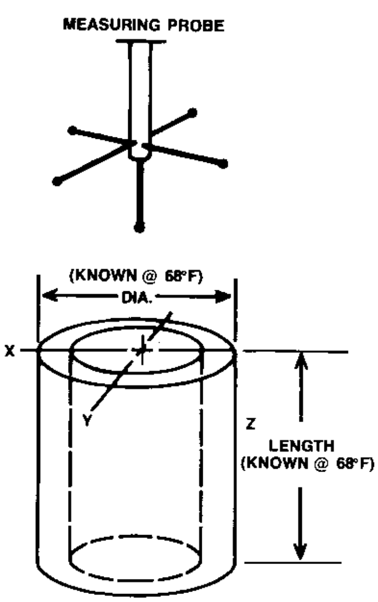


Fig. 6



MASTER FOR CHECKING SQUARENESS
VARIATIONS AND TRANSDUCER VARIATIONS

Fig. 7

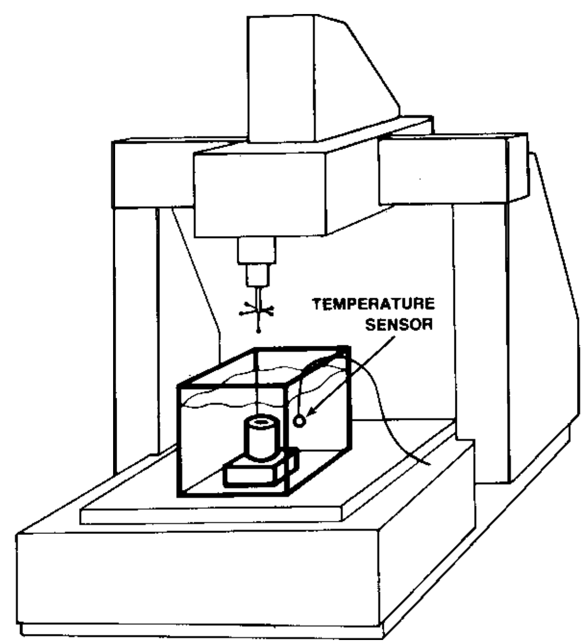


Fig. 8

A COMPUTER CONTROLLED SYSTEM TO CALIBRATE MICROWAVE POWER SENSORS AND ATTENUATORS

Mike Cuevas and John L. Minck

1. MICROWAVE POWER IS EXPENSIVE.

Power at microwave frequencies is expensive, the higher the power! the higher the price. For example, the typical price of a one watt amplifier at x-band is in the neighborhood of $5K. But a two watt amplifier can cost as much as 50% more than its one watt counterpart. Double the frequency and the price can also easily double.

Vendors want to ensure that their products - be it an FET, an amplifer, or an entire system are meeting their power specifications. Their future business depends on that. On the other hand, users of power devices want to ensure that they are getting what they are paying for. Hence, the need to measure power, and measure it accurately.

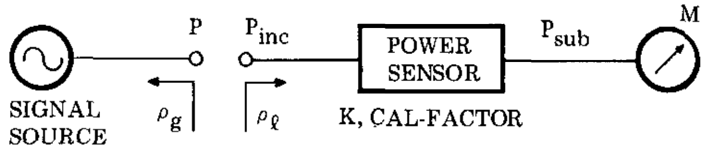
2. HOW POWER MEASUREMENTS ARE MADE.

There are many ways to determine what the power level is at a specific test port. One could use a detector and calibrate its voltage output in terms of its power input. Or one could use a spectrum analyzer, or one could connect a resistor, of the proper value, to the test port and by measuring the temperature rise due to the power output, the power level can be calculated. But, for most power measurements, there is a simpler and far more accurate method. And that is to use a power meter with the appropriate power sensor.

3. HOW TO GET ACCURATE POWER MEASUREMENTS

Because power is one of the most fundamental microwave parameters and it is important to know its level precisely, we want to measure it as accurately as possible. To do that we need to understand what it takes to make an accurate power measurement.

Power measurements are very simple in concept, all that is necessary is a power sensor that covers the appropriate power range and frequency range and a power meter to display the power level. However, the analysis of the uncertainties involved in the measurement can get complex.



$$K = \frac{P_{sub}}{P_{inc}}, \quad M = P_{sub}(1 \pm i)$$

$$P_{inc} = \frac{P}{(1 \pm \rho_g \rho_\ell)^2}; \therefore P = \frac{M}{(1 \pm i)} \cdot \frac{1}{K}(1 \pm \rho_g \rho_\ell)^2$$

Figure 1. Element of a Power Measurement

For example, in figure I, to *determine* what the actual power level, P, is at the output of the signal source we need to consider the following main three factors:

a) What the Cal-factor K is for the power sensor

b) The accuracy to which K is known

c) ρ_e, the reflection coefficient of the power sensor

To a lesser degree, we also need to consider the following factors:

d) ı, the instrumentation accuracy of the meter

e) Wear and tear on the connector

f) Undetected defects on the connector bead

g) Unnoticed changes in K due to damage or overpower

Consideration of the above factors indicates that to have continuous confidence in a given power measurement system, it is essential that, at the very least, the factors that contribute the most to the measurement uncertainty be periodically calibrated. The factor that gives the most information about the general health of a power sensor is its Cal-factor. For example, a drastic change in Cal- factor is a sure sign of a defective sensor. Hence the emphasis on periodically calibrating the Cal-factor of power sensors.

4. A NEW SYSTEM TO CALIBRATE POWER SENSORS AN!, ATTENUATORS

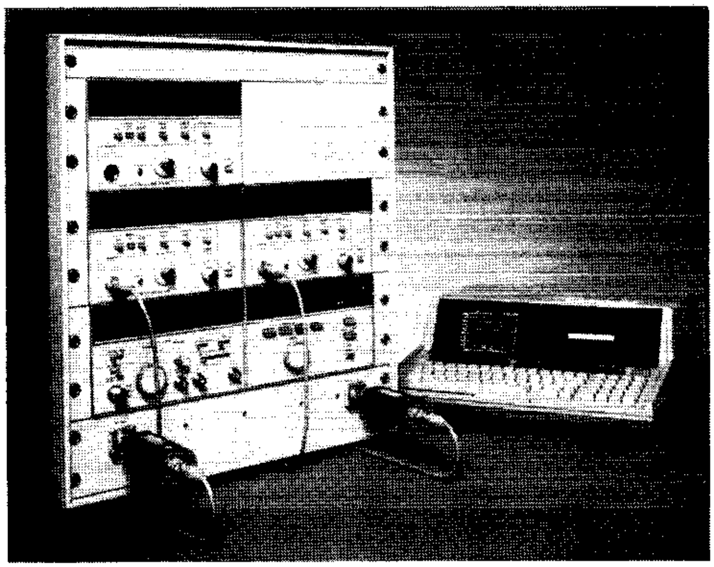


Figure 2. Computer controlled system to calibrate microwave power sensors and attenuators.

HP is introducing a new automatic calibration system with five frequency band options consisting of a power meter based reflectometer to calibrate HP power sensors. It also calibrates attenuators to an accuracy exceeded only by error correcting automatic network analyzers.

Because the system can measure the reflection coefficient of the device under test, it can determine the mismatch uncertainity. Since the actual performance of the key components such as the coupler and the "standard" sensor are stored in memory, the measurement uncertainty can be calculated and traced to higher echelons.

A version of these systems is used by key HP service facilities to calibrate customers power sensors.

5. POWER SENSOR CALIBRATION

For power sensor calibration, the basic technique is to measure the power from a carefully controlled source, first with a "standard" power sensor that has bee" calibrated by a higher echelon standards lab, and then compare this measurement to a power measurement made with the sensor being calibrated.

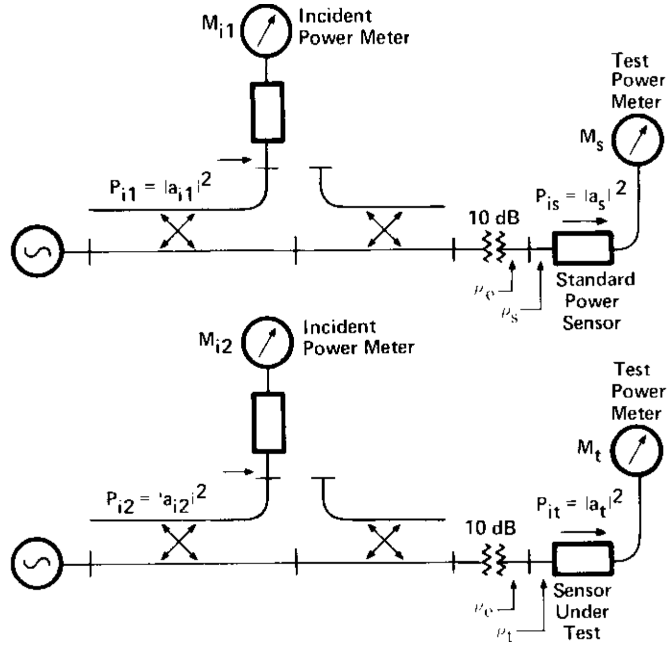


Figure 3. Procedure for Cal Factor Calibratior

What we want to know is the calibration factor Kb of the sensor under test

By definition $K_b = \frac{P_{sub}}{P_{inc}}$ **and** $P_{sub} = \frac{M}{(1\pm i)}$

from figure 3 $K_b = \frac{M_t}{(1\pm i_t)} \frac{1}{P_{it}}$ and $K_s = \frac{M_s}{(1\pm i_s)} \frac{1}{P_{is}}$

$$K_b = K_s \frac{M_t}{M_s} \frac{(1\pm i_s)}{(1\mp i_t)} \frac{P_{is}}{P_{it}} \qquad (5.1)$$

But, we need to express P_{is} and Pit in terms of their respective incident power meter readings. Using S-parameter analysis we get

$$P_{is} = |a_s|^2 = |a_{i1}|^2 \frac{T_e^2}{(1\pm\rho_e \rho_s)^2}$$

$$P_{it} = |a_t|^2 = |a_{i2}|^2 \frac{T_e^2}{(1\pm\rho_e \rho_t)^2}$$

but

$$|a_{i1}|^2 = P_{i1} = \frac{M_{i1}}{(1\pm i_1) K_1}$$

$$|a_{i2}|^2 = P_{i2} \quad \frac{M_{i2}}{(1\pm i_2) K_1}$$

$$K_b = K_s \frac{M_t}{M_s} \frac{M_{i1}}{M_{i2}} \frac{(1\pm \rho_e \rho_t)^2}{(1\pm \rho_e \rho_s)^2} \frac{(1\pm i_s)}{(1\pm i_t)} \frac{(1\pm i_2)}{(1\pm i_1)} \qquad (5.2)$$

Where:

K_b = Cal-factor of sensor under test

K_s = Cal-factor of "standard" sensor

M_t = Reading of test power meter when sensor under test is connected to it.

M_s = Reading of test power meter when "standard" sensor is connected to it.

M_{i1} = Reading of incident power meter when transmitted power is measured with "standard" sensor.

M_{i2} = Reading of incident power meter when transmitted power is measured with sensor under test.

ρ_e = Test port source match

ρ_s = Reflection coefficient of "standard" sensor

ρ_t = Reflection coefficient of sensor under test

T_e = Transmission from the incident power sensor to the test power sensor.

$i_s = i_t$ = Accuracy of test power meter when "standard" sensor (is) or sensor under test (it) is connected to it.

$i_1 = i_2$ = Accuracy of incident power meter when transmitted power is measured with "standard" sensor (i1), or sensor under test (i2).

6. ACCURACY OF POWER SENSOR CALIBRATION

The whole purpose of deriving the above equation that expresses the calibration factor of the sensor under test, Kb, as a function of the calibration factor of the "standard" sensor, Ks, plus mismatch uncertainties and power meter instrumentation uncertainty is to calculate the uncertainty in Kb.

This uncertainty is easily derived from equation 5.2, and is

$$U_{K_b} = \left[\left(\frac{U_{K_s}}{100}+1\right)\left(\frac{1\pm\rho_e\rho_t}{1\mp\rho_e\rho_s}\right)^2\left(\frac{1\pm i_2}{1\mp i_1}\right)\left(\frac{\text{[illegible]}}{1\mp i_t}\right) - 1\right] 100 \quad (6.1)$$

in %

where:

		Typical Values at X-band for 8481A
U_{K_b} =	Cal-factor uncertainty of the power sensor being calibrated in %	?
U_{K_s} =	Cal factor uncertainty of the Standard Sensor	1.9%
ρ_t =	Reflection coefficient of sensor under test	0.05
ρ_s =	Reflection coefficient of the Std. sensor	0.026
ρ_e =	Test port reflection coefficient including effect of 10 dB coupler	0.08
i =	Power meter uncertainty, includes $(1\pm i_2)(1\pm i_s)/(1\pm i_1)(1\pm i_t)$ plus effects of noise and mismatch of reference oscillator and sensor	0.5%

Using the typical value for the 8481A in equation 6.1 will give an estimate of the magnitude of the uncertainties expected:

$$U_{K_b} = \left[\left(\frac{1.9}{100}+1\right)\left(\frac{1+0.08X0.05}{1-0.08X0.026}\right)^2 (1.005)-1\right] 100$$

in %

$$U_{K_b} = \left[(1.019)\;(1.012)\;(1.005)-1\right]100$$

Std. sensor Cal-Fact Uncert — Mismatch — Instrum.

U_{K_b} = 3.64% Worst Case

However, since the elements of the uncertainty, (Cal-factor accuracy of the standard sensor, mismatch, and instrumentation) are independent of each other, combining them in a worst case manner is very unrealistic. A more realistic and generally accepted method of combining the individual uncertainties is in a root sum of the squares (RSS) fashion:

$$U_{K_b\,RSS} = \sqrt{1.9^2 + 1.2^2 + 0.5^2}$$

$$U_{K_b\,RSS} = 2.3\%$$

7. ATTENUATION CALIBRATION

Attenuation calibrations are made by taking the ratio of the transmitted power to the incident power. They are very accurate because power sensors have very low SWR (typically better than 1.1 in x-band). Therefore, mismatch uncertainty is low, plus, the 436A is extremely linear and accurate. Note that the "se of two power meters permit* a measuring dynamic range of over 70 dB even when either power sensor only has a 40 dB range. The reason is, of course, that the incident power meter can be used to adjust the generator's output range extremely accurately over a 40 dB range which then gets added to the 40 dB detection range of the test power sensor.

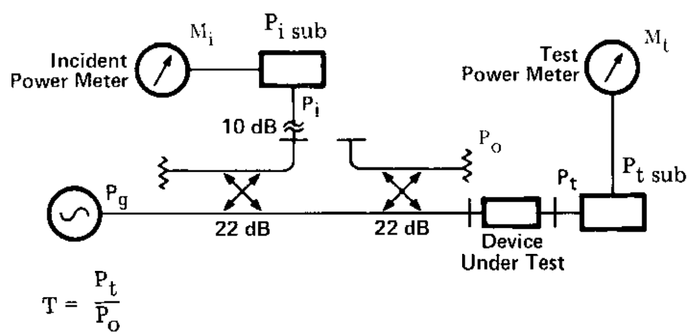


Figure 4. Procedure for attenuation calibration

8. ACCURACY OF ATTENUATION CALIBRATION

The two main contributors to attenuation measurement uncertainty with this system are mismatch and instrumentation uncertainty. For ease of analysis these two uncertainties will be treated separately and then combined to determine the overall uncertainty.

a) Mismatch

Mismatch uncertainties are due to the reflections and re-reflections at each connection. These reflection* change the amplitude of the incident wave so that it is different from what it would be for a system that had a zero-reflection generator, device under test, and Power sensor. There are two elements to the mismatch uncertainty. One, when the system is being calibrated and the test Power sensor is connected directly to the test port of the coupler (no device under test). The other element of the mismatch uncertainty is when the device under test is connected. This gives rise to re-reflection*:

a) From the input of the device under test and the signal source

b) From the test sensor and the output of the device under test.

c) From the test sensor and the signal source through the device under test.

These mismatch uncertainties can be mathematically derived from flow graphs modeling of the attenuation measurement process.

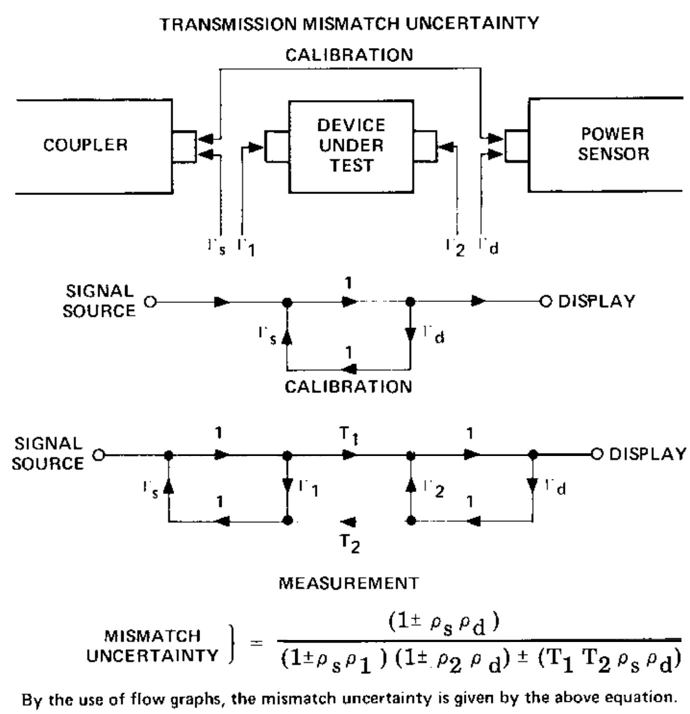


Figure 5. Flow Graph Analysis of mismatch uncertainties measurement

b) Instrumentation Uncertainty

To make an attenuation measurement, three power ratios are taken:

One, during calibration, the ratio of the transmitted power to the incident power, without a device under test is taken and stored into memory. This ratio determines the 0 dB reference from which the attenuation of the device under test is measured. By setting the 0 dB reference across the frequency range of interest, the system variations with frequency are taken into account.

Two, during the measurement, the ratio of the transmitted power to the incident power, with the device under test inserted is again taken and stored into memory.

Three, the ratio of the above two ratios determine) the attenuation of the device under test. In general:

$$T = \frac{P_t}{P_i}$$

but $P_t = \frac{P_{t\,sub}}{K_t}$, $P_i = \frac{P_{i\,sub}}{K_i}$, and $P_{sub} = \frac{M}{(1 \pm i)}$

$$T = \frac{M_t}{M_i} \cdot \frac{(1 \pm i_i)}{(1 \pm i_t)} \cdot \frac{K_i}{K_t}$$

During calibration

$$T_c = \frac{M_{tc}}{M_{ic}} \frac{(1 \pm i_{ic})}{(1 \pm i_{tc})} \cdot \frac{K_i}{K_t}$$

During measurement

$$T_m = \frac{M_{tm}}{M_{im}} \frac{(1 \pm i_{im})}{(1 \pm i_{tm})} \frac{K_i}{K_t}$$

To determine attenuation

$$\text{Attenuation} = \frac{T_m}{T_c}$$

$$\text{Attenuation} = \frac{M_{tm}}{M_{tc}} \frac{M_{ic}\,(1 \pm i_{tc})\,(1 \pm i_{im})}{M_{im}\,(1 \pm i_{tm})\,(1 \pm i_{ic})}$$

c) Total Uncertainty in Attenuation Calibration

Combining the uncertainties due to mismatch and instrumentation we get

$$U_{att\ \text{in}\ \%} = \left[\frac{(1 \pm \rho_s \rho_d)}{(1 \pm \rho_s \rho_1)(1 \pm \rho_2 \rho_d) \pm (T_1 T_2 \rho_s \rho_d)} - 1 \right] 100 + \left[\frac{(1 \pm i_{tc})\,(1 \pm i_{im})}{(1 \pm i_{tm})\,(1 \pm i_{ic})} - 1 \right] 100 \qquad (8.3)$$

where:

		Typical Values at **x-band**
ρ_s =	Effective source match at the coupler output	0.12
ρ_d =	Reflection coefficient of test sensor	0.07
ρ_1 =	Port 1 reflection coefficient of the device under test	--
ρ_2 =	Port 2 reflection coefficient of the device under test	--
T_1 =	Forward transmission coefficient of the device under test	--
T_2 =	Reverse transmission coefficient of the device under test ($T_1 = T_2$)	--
$i_{tc} = i_{tm}$ =	Accuracy of test power meter during calibration (i_{tc}) and during measurement (i_{tm})	0.5%
$i_{ic} = i_{im}$ =	Accuracy of incident power meter during calibration (i_{ic}) and during measurement (i_{im})	0.5%

The main contributor to the attenuation uncertainty is mismatch. Notice in the above expression that the contribution due to instrumentation is (should be) much smaller than indicated. This becomes apparent upon closer examination of the term that expresses the uncertainty due to instrumentation. In the numerator, we have the uncertainty of the test power meter during calibration times the uncer tainty of the incident power meter during the measurement. While in the denominator we have the uncertainty of the test power meter during measurement times the uncertainty of the incident power meter during calibration. But the test power meter is the same for both calibration and measurement. Therefore, if it reads high, let's say, during calibration, it will also ready high during the measurement. Because the power levels will be nearly the same for attenuation levels up to 30 dB, therefore $(1 + itc) \approx (1 + itm)$ and their ratio will be very close to one. The same argument holds true for the incident power meter when the attenuation level being measured is small, 10 dB, and therefore the power meter does not change ranges from calibration to measurement.

To get an estimate of the magnitude of the uncertainties expected for attenuation calibration, let's assume that we are going to calibrate a 20 dB pad with a reflection coefficient of 0.1 at either port. Using these numbers and the typical values listed, when we plug them in equation 8.3; we get:

$$U_{att \text{ in } \%} = \left[\frac{(1 + .12 \times .07)}{(1 - .12 \times .1)(1 - .07 \times .1) - (.1 \times .1 \times .12 \times .07)} - 1 \right] 100 + 1.5$$

$$U_{att \text{ in } \%} = 4.29\%$$

$$U_{att \text{ in dB}} = 20 \log (1.0429)$$

$$U_{att \text{ in dB}} = 0.365 \text{ dB worst case}$$

As in the case of power sensor calibration, the elements of the attenuation calibration (mismatches and instrumentation) are indepencent of each other, combining them in a worst case manner is very unrealistic. A more realistic method of combining them is in a root sum of the square fashion.

$$U_{att \text{ in dB, RSS}} = \sqrt{\left[20 \log \left(1 + \sqrt{(\rho_s \rho_d)^2 + (\rho_s \rho_i)^2 + (\rho_d \rho_2)^2 + (T_1 T_2 \rho_s \rho_d)}\right) \right]^2 + \left[20 \log (1 + i) \right]^2}$$

$$U_{att \text{ in dB, RSS}} = \sqrt{\left[20 \log \left(1 + \sqrt{(7.1 \times 10^{-5}) + (14.4 \times 10^{-5}) + (4.9 \times 10^{-5}) + 1 \times 10^{-8}}\right) \right]^2 + \left[20 \log (1.05) \right]^2}$$

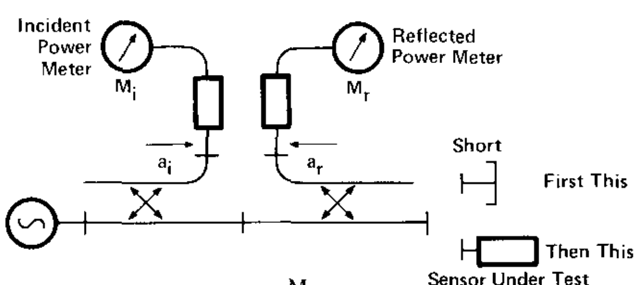
$$U_{att \text{ in dB, RSS}} = \sqrt{0.14^2 + 0.129^2}$$

$$U_{att \text{ in dB, RSS}} = 0.191 \text{ dB}$$

Actual Result: 20 dB ± 0.191 dB

9. REFLECTION MEASUREMENTS

Reflection measurements are made by taking the ratio of the incident power to the reflected power. Having the capability of measuring the reflection coefficient of the device under test allows us to calculate the mismatch uncertainty. Because the parameters of the key components of the system are stored in memory, plus the knowledge of mismatch uncertainty gives the computer all the necessary information to calculate the overall measurement uncertainty for each measurement.



$$\rho = \frac{M_r}{M_i}$$

Figure 6. Procedure for Measuring Reflection

10. ACCURACY OF REFLECTION MEASUREMENTS

The two main sources of uncertainty in reflection measurements are the coupler performance, which includes reverse coupler directivity and source match, and the instrumentation uncertainty. For ease of analysis, these two uncertainties will be treated separately and then combined to determine the overall uncertainty.

a) Coupler Performance

Using flow graph analysis it can **be shown that the error in** reflection measurements due to the coupler performance is:

$$\Delta \rho = A + B\rho + C\rho^2$$

$\Delta\rho$ = Magnitude of reflection coefficient uncertainty

A = Directivity of reverse coupler

B = Calibration and tracking errors which include effects of forward and reverse coupler directivity and mismatch between device under test and coupler source match.

C = Effective source match for coupler

ρ = Reflection coefficient of D.U.T.

Notice that the greater the reflection coefficient of the D.U.T. the greater the uncertainty.

b) Instrumentation uncertainty

To make a reflection measurement, as in attenuation measurements, three power ratios are taken:

One, during calibration, the ratio of the reflected power to the incident power is taken with a short ($\rho c = -1$) connected at the coupler test port. The data is stored in memory. This ratio determines the reference, 100% reflection, from which the reflection coefficient of the device under test is measured. By setting the 100% reference across the frequency range of interest, the system variations with frequency are taken into account.

Two, during the measurement, the ratio of the reflected power to the incident power is again taken, with the device under test connected to the coupler test port. This ratio, as a function of frequency, is stored in memory.

Three, the ratio of the above two ratios determines the reflection coefficient of the device under test.

Using the same analysis as the one used for the instrumentation uncertainty for attenuation measurements, the instrumentation uncertainty, Ur, for reflection measurements is:

$$U_r = \frac{(1 \pm i_{rc})\ (1 \pm i_{im})}{(1 \pm i_{rm})\ (1 \pm i_{ic})}$$

c) Total Uncertainty in Reflection Measurements

Combining the uncertainties due to coupler performance and instrumentation we get:

$$U_R\% = \frac{(A + B\rho + C\rho^2)}{\rho} 100 + \left[\frac{(1 \pm i_{rc})\ (1 \pm i_{in})}{(1 \pm i_{rm})\ (1 \pm i_{ic})} - 1 \right] 100$$

11. SYSTEM CAPABILTIES

a) Sensor calibration

With the E-40, the following HP power sensors can be calibrated:

8481A 8482A 8484A

8481H 8482H 8485A

8478B 478A X-P-K 486A

in coax

From 100 MHz to 26.5 GHz in 3 bands

100 MHz to 2.0 GHz
2 GHz to 18.0 GHz
18 GHz to 26.5 GHz

and in waveguide

From 8.2 to 26.5 GHz in 3 bands

X = 8.2 to 12.4 GHz
P = 12.4 to 18.0 GHz
K = 18.0 to 26.5 GHz

b) Attenuator Calibration

The 436A-E40 also calibrates coaxial attenuators

From 100 MHz to 26.5 GHz (in 3 bands)

with a dynamic range of

70 dB to 18.0 GHz and 35 dB to 26.5 GHz

12. 436A-E40 BENEFITS

The main benefit* of the 436A-E40 are

a) It provides traceability. Traceability is provided by the 'Reference Standard" sensor. The system is now configured, with standard sensor calibrated in Hewlett-Packard's Metrology Lab. The Hewlett-Packard Metrology Lab in turn gets its standards calibrated by the U.S. National Bureau of Standards. But, of course, traceability can be established to any primary standard that the user wishes. Attenuator traceabilty is provided by the power meter*.

b) It provides self sufficiency. Sensors and attenuators can be calibrated internally. The advantage of internal calibration capabilities is that the user can perform the calibration immediately. Plus the user will probably calibrate more often, therefore, catch defective devices that otherwise might have gone unnoticed.

c) It increases productivity. It takes an average of 5 minutes to calibrate a sensor at 20 frequencies, including the measurement of reflection and the completion of the calibration report.

d) It provides reports in useful formats:

o Tabular

o Graphs

o Includes uncertainty of each calibration point, date of calibration, serial number of "standard" sensor, and initials Of operator.

e) Easy to operate. The friendly software guides the operator thru statements displayed on the computer CRT as to what the steps are for each calibration.

f) Accurate results. As with any system where many variables, including operator's skill, contribute to the overall uncertainty, the precise system uncertainty of the 436A-E40 is relatively easy to determine mathematically, but very time-consuming to verify with all the possible permutations of the system variables. For this reason, we only specify the typical performance. We use the equations previously derived to calculate the measurement uncertainty. This uncertainty is listed in the calibration report.

The actual measurement results obtained with the 436A-E40 are very close to those obtained with a Network Analyzer. The main difference is the magnitude of the uncertainty band. In general, the calculated worst case uncertainty of the 436A-E40 is about twice of that obtained with a" error correcting automatic Network Analyzer.

13. CALIBRATION WORK LOAD TO JUSTIFY AN E-40 SYSTEM

The average price of a 436A-E40 system is i" the order of $50,000. The obvious question is then, how big of a calibration work load will justify a" E-40 system?

The minimum typical annual work load that would justify a 436A-E40 system would consist of a combination of 50 power sensors, 50 pads, and 25 step attenuators, or more., that need to be calibrated on an on-going basis. With this type of work load, the annual calibration bill, if the calibration is done by HP is in the order of $18K per year.

	Power Sensors	Pads	step Attenuators
Recalibration	$75	$50	$150
Paperwork	30	30	30
Shipping	10	10	10
Downtime	25	10	40
	$140	$100	$230

Yearly calibration cost of 50 sensors:	$7.00K
Yearly calibration cost of 50 pads:	5.00K
Yearly calibration cost of 25 step attenuators:	5.75K
Total Cost of Calibration:	$17.75K

Cost of calibrating E-40:	$1.0K
Cost of maintenance E-40:	2.0K
Operation cost based on above workload: (3 days @ $200/day)	0.6K
Total cost of Ownership/year	$3.6K

Net savings = cost of calibration
- cost of ownership
= $17.75K - $3.6K

Net savings = $14.15K

Average cost of E-40 = $50K

Pay off period = $\frac{\$50K}{\$14.15K}$

= 3 years 6 months
(faster if work load greater)

This analysis does not include the calibration of other devices such as cables and airlines, or the measurment of transistors, etc. It does not include either the intangible benefits such as faster turn-around time, and calibrations made more often.

References: Hewlett-Packard Application Note 64-1

Hewlett-Packard Application Note 64-2

MULTI-PORT CHARACTERISTICS

A. L. Lance
TRW Operations and Support Group
One Space Park
Redondo Beach, California 90278

ABSTRACT

This paper presents a detailed analysis of multi-port structures used as network analyzers to determine phase and magnitude of impedance (reflection coefficient) from measurements of magnitude only. Physical interpretations using phasor signals are used to illustrate, describe and compare mathematical solutions, complex plane representation and the corresponding magnitude measurements of voltage or power.

INTRODUCTION

The basic relationships of the incident voltage wave, E_i, and the reflected voltage wave, E_r, as measured in the lossless netowrk shown in Figure 1a, are used to define microwave propagation parameters. Specifically, the parameters can be defined in terms of the detected signals and not the absolute signal magnitudes in the main line. As an example, the probe in this structure might be decoupled by 20 dB.

The maximum limits of uncertainty in the measurement of E_i occur for the in-phase (0°) and out-of-phase (180°) relationships and have been defined as plus mismatch error, K, and minus mismatch error, K', as illustrated in Figure 1b[1].

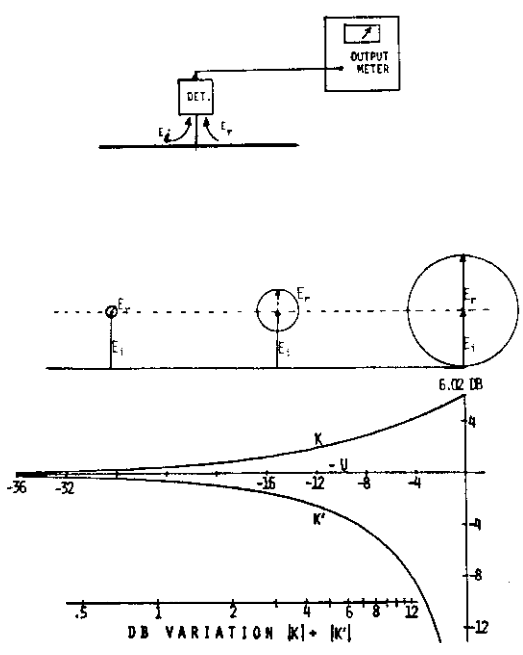


FIGURE 1. Basic Phasor Relationships of Any Two Signals Expressed in dB. E_r Restricted to Values Between Zero and E_i.

For the in-phase condition,

$$K = 20 \log \left(\frac{E_i + E_r}{E_i}\right) = 20 \log (1 + |\Gamma_\ell|) \tag{1}$$

since the reflection coefficient is defined as E_r/E_i

For the 180° out-of-phase condition,

$$K' = 20 \log \left(\frac{E_i - E_r}{E_i}\right) = 20 \log (1 - |\Gamma_\ell|) \tag{2}$$

The standing wave ratio in dB, S, is the variation between K and K'.

The dB difference between the two voltages is

$$-U = 20 \log \left(\frac{10^{S/20} + 1}{10^{S/20} - 1}\right) = 20 \log \left(\frac{VSWR + 1}{VSWR - 1}\right) \tag{3}$$

or

$$U = -20 \log |\Gamma| \tag{4}$$

which is the microwave parameter defined as return loss for the representation in Figure 1.

The parameters K and K' can also be calculated from a measurement of the dB variation, S.

$$K = 20 \log \left[\frac{2 \times 10^{S/20}}{10^{S/20} + 1}\right] \tag{5}$$

$$K' = 20 \log \left[\frac{2}{10^{S/20} + 1}\right] \tag{6}$$

The dotted circle in Figure 2 illustrates the phasor relationships and the corresponding magnitude relationships that result if a variable perfect short circuit, (Γ = I), connected at the measurement plane, is adjusted over a distance corresponding to 160" phase shift.

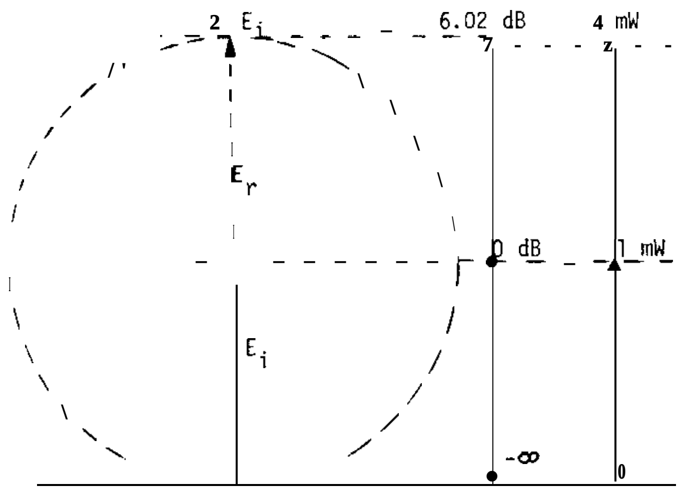


FIGURE 2. Phasor Relationships and Corresponding Magnitude for Short Circuit Variation.

The important observation is that at the maximum, Equation 1 gives

$$K = 20 \log (1 - |\Gamma|) = 6.02 \text{ dB} \tag{7}$$

and at the minimum

$$K' = 20 \log (1 - |\Gamma'|) = -\infty \tag{8}$$

These values are also shown at the right hand axis in Figure lb.

If the short circuit is not perfect, or if there is a loss between the measurement plane and the probe, the result will be a circle inside this dotted circle since E_r will not equal E_i.

A Three-Port Network Analyzer Using Amplitude Measurements

The network of Figure 1 can be constructed to form a network analyzer for measuring reflection coefficient. Assume that a reflectionless loss is added as illustrated in Figure 3a. This structure is analogous to each reflective port (3, 5 and 6) of the six-port, as defined by Engen[2]. However, this initial discussion does not include the direct correlation of six-port equations and concepts because the absolute values of the wave amplitudes a2 and b_2 are not established. The complex ratio, a_2/b_2, is obtained by measurements of the signals at the detector and referred to the measurement reference plane.

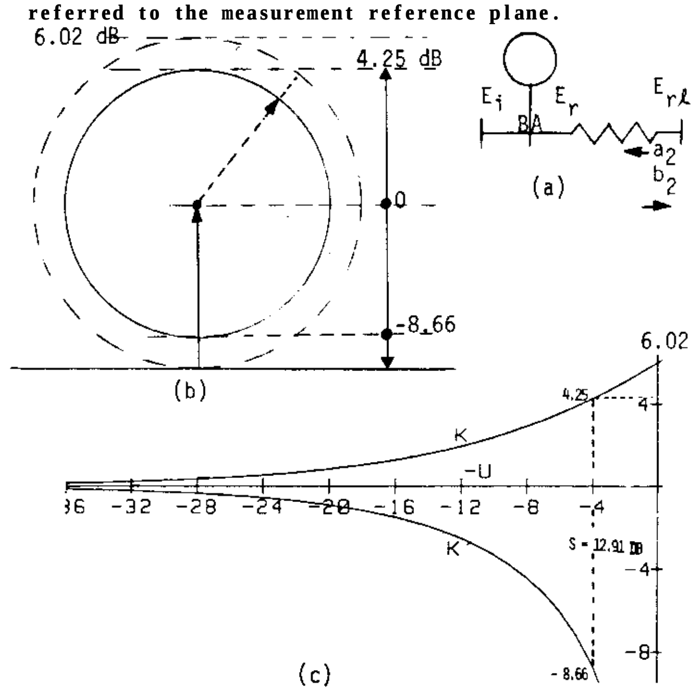


FIGURE 3. (a) A Three-Port Impedance Measurement System.
(b) Phasor Relationships and Corresponding Assumed Magnitudes.
(c) Relationships to Basic Theory.

Engen defined a q-point as -B/A which places the q-point someplace on the dotted circle that represents the results which would have been obtained if -B/A = 1, i.e., the true variation produced by the short circuit at the reference plane and which must now be represented by the solid circle.

$$E_o = E_i + \tau E_{r\ell} = E_i (1 + \tau \Gamma_\ell) \tag{9}$$

where τ is the transmission coefficient corresponding to the round trip loss between the probe and the measurement plane.

The single port of a six-port is

$$b_3 = Bb_2 + Aa_2 \tag{10}$$

$$b_3 = Ab_2 (\Gamma_\ell - q) \tag{11}$$

where it is noted that -B/A is a measure of the dB difference (round trip loss) between the forward and reverse signals at the detector, as indicated in Figure 3b.

Figure 3c illustrates the phasor representation which results if a variable short circuit is phased a distance corresponding to 180° rotation of the signals as previously discussed. The corresponding magnitudes are shown in Figure 3c and d for the assumed reflectionless 2 dB loss.

The solid circle shown in Figure 3c represents a reflection coefficient, $\Gamma = 1$, as see" at the detector. The total variation (12.91 dB) that can possibly occur illustrates the compressed measurement range which is described in six-port applications. This illustrates the basic principles of measurements using interferring signals. Recall that the dynamic range of the system show" in Figure 1 might be 60 dB or greater depending upon the particular hardware available.

Determination of the constants A and B of the six-port, or the complex τ in this discussion, is called the calibration. Figure 3 illustrates that either system can be calibrated by obtaining the variation S, in dB, or voltage or power when a variable short circuit ($\Gamma = 1$) is phased to produce the maximum and minimum. VAriations offset short circuits can be used and the indicated phasor relationships can be obtained by calculations. In this case, the return loss of the different short circuits must be taken into account. In the example of Figure 3d, the maximum (K) is 4.25 dB above the E_i reference, as calculated from S = 12.91 dB. The return loss between the two signals -U is 4 dB. The center of the circle (which is the Z_0 load reference at the detector for the port of the six-port, or E_i in Figure 3a) is 4.25 below the maximum. In this illustration, the Z_0 reference power is 1 milliwatt. Observe that this particular representation shows that 6.02 dB - 4.25 dB = 1.77 dB, which is a ratio of 1.22603. The phase angle for the reference short is obtained by connecting the fixed reference plane short (which must have the same return loss characteristics corrected as the short circuit(s) used in system calibration) and the phase angle is established as noted in Figure 4.

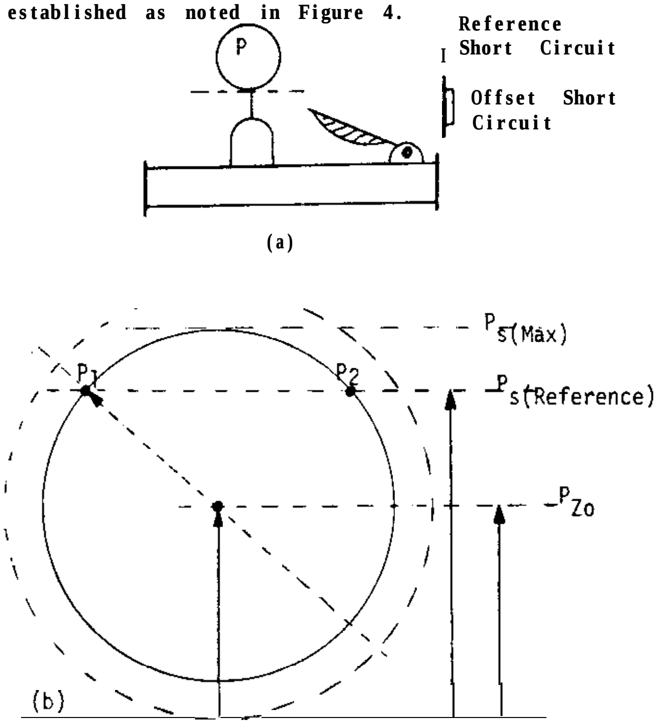


FIGURE 4. (a) Three-port - Forward signal always larger than the reflected signal. Offset short or dielectricas shown, used to find quadrant location of $P_{s(Reference)}$.
(b) Corresponding phasors and magnitudes.

The slight offset short can be connected and the resulting power level change establishes the quadrant location P_1 or P_2, shown in Figure 4. The insertion of a lossless (or characterized) dielectric phase shift device can also be used for this purpose. as illustrated in Figure 5.

Figure 5 illustrates that a" elementary measurement technique can be established using perturbation techniques. The calibration and phase reference are established at Plane 1 as previously set forth. The load is connected to obtain P_{11} and the dielectric vane is inserted to obtain a power level change in P_{11} merely to locate the quadrant then it is removed. A short section, reflectionless, precision line (properly characterized) can be inserted to obtain P_2, as shown, and the phase angle change is established. The load is connected and the change in power level can be used to establish the magnitude of Γ_ℓ, and, thereby, making it possible to find the complex Γ_ℓ. This is merely an illustration of the technique and the necessary mathematical calculations are not shown. One can repeat this total procedure for a number of short circuit displacements (with corrections) and establish the circle representing the short and also Γ_ℓ.

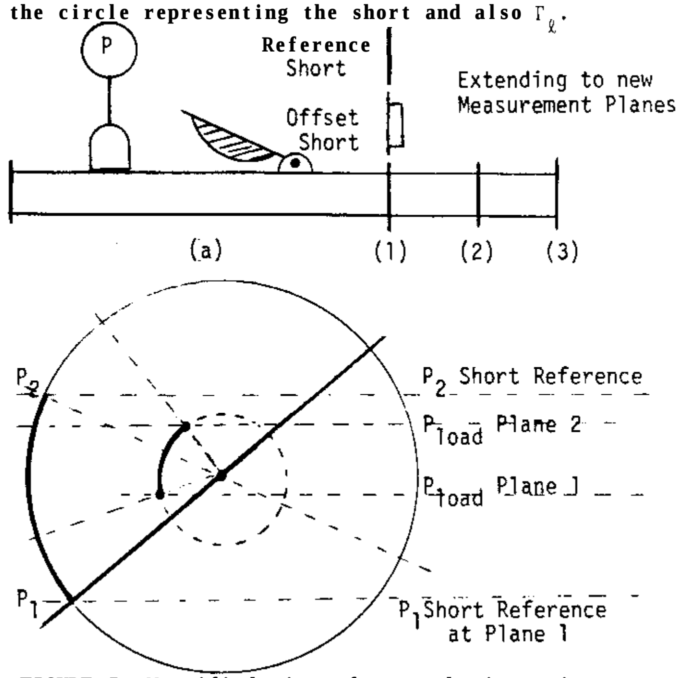


FIGURE 5. Magnified view of perturbation using precision characterized extensions which can also be used in applications of basic six-port concepts. Reference short and offset and dielectric used as set forth in locating quadrants.

Basic six-port concepts can be applied using the planes 1, 2 and 3, as shown in Figure 5 and also in Figure 6.

A Four-Port System

The four-port structure in Figure 6 represents the reference power P_4 and a single reflected port of a six-port. The corresponding phasor diagrams and power levels are shown to correspond to the previous three-port characteristics.

The equations that describe the system are

$$b_3 = Aa_2 + Bb_2 \tag{12}$$

$$P_3 = |Aa_2 + Bb_2|^2 \tag{13}$$

$$P_3 = |A|^2 |b_2|^2 |\Gamma_\ell - q_3|^2 \tag{14}$$

since by definition, $\Gamma_\ell = a_2/b_2$ and $q_3 = -B/A$ as defined by Engen[2].

$$b_4 = Ca_2 + Db_2 \tag{15}$$

$$P_4 = |Ca_2 + Db_2|^2 \tag{16}$$

$$P_4 = |D|^2|b_2|^2|1 - \Gamma_\ell \Gamma_g|^2 \tag{17}$$

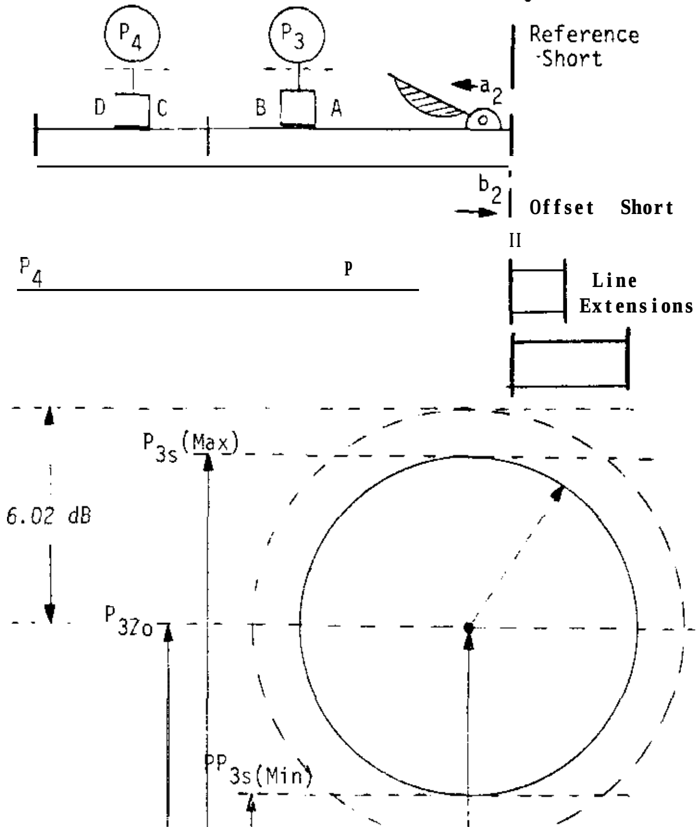


FIGURE 6.

Calibration of the system can be performed by establishing the dB variation, S, and phase angle as previously explained.

Also, one can establish P_{3Z_0} which is the P_3 power level when a Z_0 load is effected at the measurement plane. Then, perfect offset shorts, or a perfect variable short circuit, can be used to establish the $P_{3(max)}$ and $P_{3(min)}$ values as illustrated. Calibration values can be established, as previously set forth, coupled with the fact that b_2 can be established by measurement at the measurement plane.

Engen has shown that the solution for obtaining Γ_ℓ is obtained from the intersection of thress circles in the complex plane[2,3]. The centers of the circles, q_3, q_5 and q_6, are given by -B/A, -F/E and -H/G and -E/A is as shown and previously evaluated. The radii of respective circles are proportioned to $\sqrt{P_3/P_4}$, $\sqrt{P_5/P_4}$ and $\sqrt{P_6/P_4}$ if C = 0, which establishes q_4 at infinity, P_5 and P_6 of additional ports.

Consistent with the previous discussions on techniques of calibration and locating phase angles and the particular quadrant where Γ_ℓ is located, Figure 6 also indicates that precision sections of line (properly characterized) can be used to obtain the q-points and also to obtain a circle representing Γ_ℓ. It is also noted that b_2 can be measured at the reference plane and A and D can be measured.

Using only the two additional "characterized" sections shown in figure 6, the six-port measurement concepts can be applied.

The Six-Port

The basic six-port structure can be illustrated as shown in Figure 7.

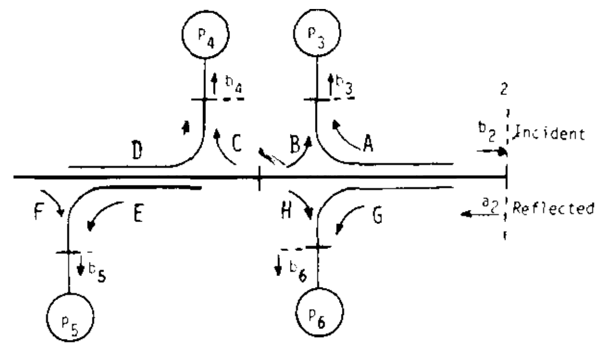


FIGURE 7. Six-Port Representation.

The equations which describe the system are

$$b_4 = Ca_2 + Db_2 \tag{18}$$

$$b_3 = Aa_2 + Bb_2 \tag{19}$$

$$b_5 = Ea_2 + Fb_2 \tag{20}$$

$$b_6 = Ga_2 + Hb_2 \tag{21}$$

The complex constants, A, B, H, can be obtained according to the basic calibration concepts previously set forth.

In the general case, the power meter readings are expressed as

$$P_4 = |D|^2|b_2|^2|1 - \Gamma_\ell \Gamma_g|^2 \tag{22}$$

$$P_3 = |A|^2|b_2|^2|\Gamma_\ell - q_3|^2 \tag{23}$$

$$P_5 = |E|^2|b_2|^2|\Gamma_\ell - q_5|^2 \tag{24}$$

$$P_6 = |G|^2|b_2|^2|\Gamma_\ell - q_6|^2 \tag{25}$$

where $q_3 = -B/A$, $q_5 = -F/E$, and $q_6 = -H/G$, as defined by Engen[2,3]. The six-port is configured so that the q-points are nominally 120" apart.

Figure 8 represents the phasor signals at each port which result from phasing of a variable short circuit connected at the measurement plane. Specifically, at the -U = 0 right hand axis, one notes that the dotted circle represents the variation that would occur if q = 1. The solid circles indicate that the signals reflected back from the short circuit have less magnitudes that the corresponding forward signals. The magnitude of the q-values (in dB) are the corresponding values of -U, as illustrated. Each is shown with a relative difference [in dB) for convenience of illustration. Each port can be treated as previously indicated for a single reflected part

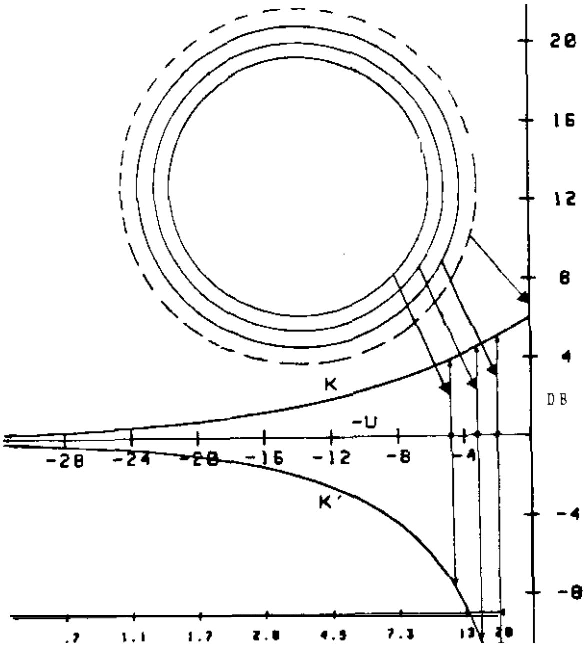


FIGURE 8 Illustration of the dB variations and the phasor relationships for the three Ports used to determine the phase and magnitude of reflection coefficient. The q-points in dB are measured from the Y-axis which represents the short circuit variation indicated by the dotted circle.

Figure 9 illustrates that the forward signals can have any phase angle (solid circle) with respect to the measurement plane. The same is true for an arbitrary load connected at the measurement plane and indicated by the small solid circles. Each of the three solid lined outside circles represent $\Gamma = 1$ and each of the inside solid circles represent Γ_ℓ.

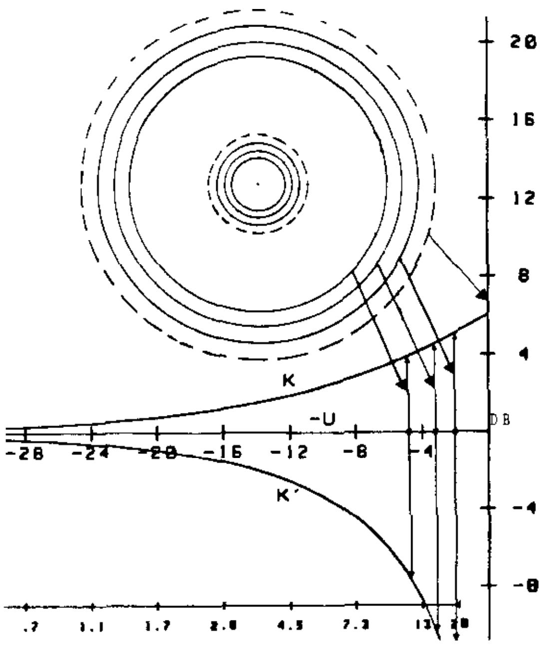


FIGURE 9. Illustration of the relative magnitudes and phasor relationships of signals in a six-port measurement system. The load reflection coefficient measured value will be an each of the'correspanding solid circles as determined by the system constants and the complex value measured.

Figure 10 illustrates the normalization into the complex gamma plane, as chosen by Engen[2,3]. The q-points are illustrated on the dotted circles as a reminder that q-points of given magnitudes would occur an the circle depending upon the operating frequency and particular complex circuit constants. The solution for Γ_ℓ is obtained from Equations and The intersection of the three circles in the complex Plane., as set forth by Engen, are illustrated. The circle centers, q_3, q_5 and q_6, are determined by calibration and the radii of the respective circles are proportional to $\sqrt{P_3/P_4}$, $\sqrt{P_5/P_4}$ and $\sqrt{P_6/P_4}$.

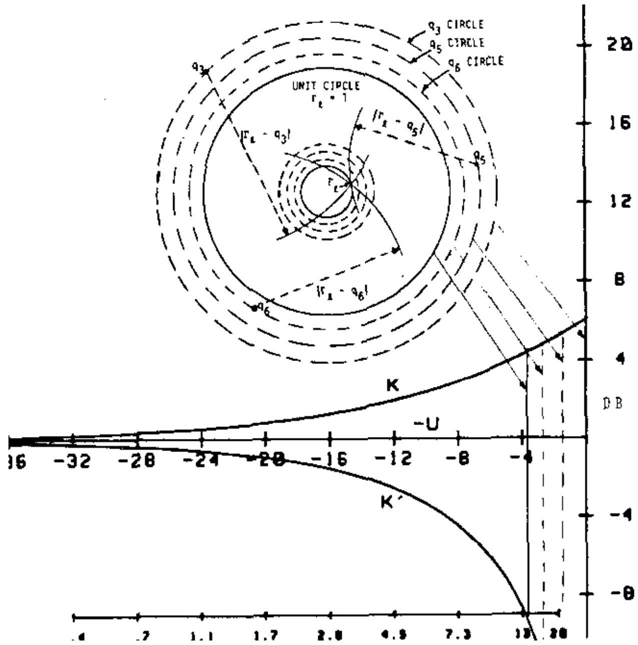


Figure 10. Complex plane representation of the six-por determination of reflection coefficient.

Figure 11 illustrates another possible complex plane normalization.

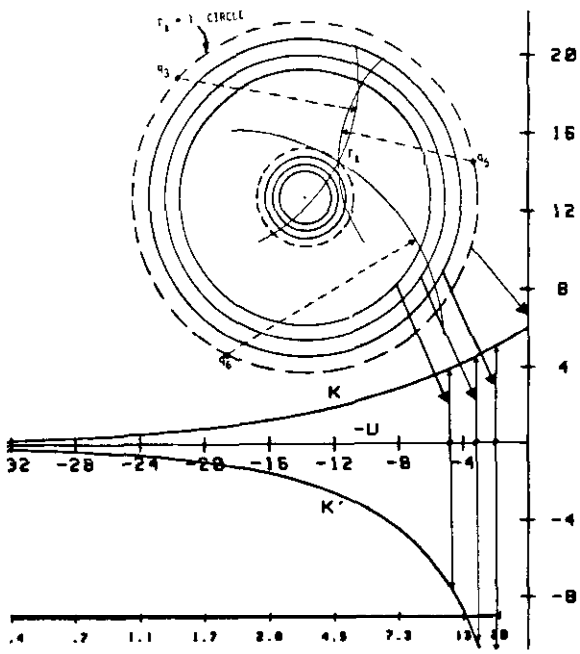


FIGURE 11. Illustration of normalization with respect to the theoretical short circuit reference.

Interesting System Characteristics

Figure 12(a) illustrates a two-probe system in waveguide with an insertable dielectric for establishing the quadrant, as previously explained. The short circuit and offset short are also used to obtain the 0° and -180° relationships of each probe referenced to the measurement plane. Sections of waveguide can be used in various measurement techniques also previously discussed. The reference planes are illustrated in Figure 12(b) with the corresponding amplitude measurements.

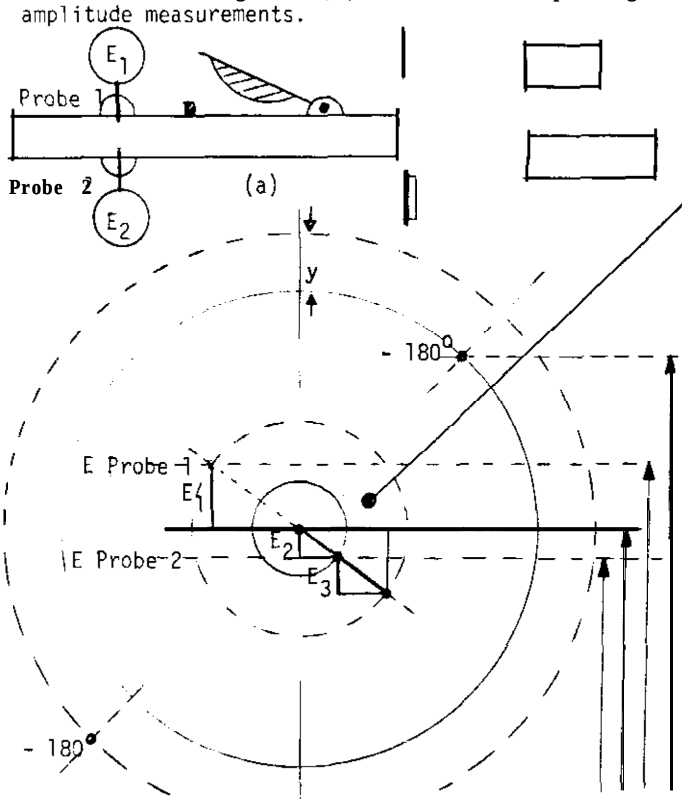


FIGURE 12. (a) Two-probe system.

(b) Illustration of phasor signals and magnitudes NORMALIZED with respect to E_{Zo}.

The value of Γ_ℓ is obtained with respect to the X-Y chart axis (E_{max} and E_{min}), then referred to the reference plane.

Only one simplified solution will be discussed. The value, y, indicated as the value between the dotted and solid circles at the in-phase Y-axis is obtained by calibration as set forth by previous techniques of obtaining the respective E_{max} and E_{min} values. This is also the value shown between b and c' as the hypotenuse of the triangle shown. Since $|E_3| = |E_1| - |E_2|$, the indicated triangle, can be established then the triangle involving Γ_ℓ and E_2 can be solved, thereby establishing the magnitude and phase of Γ_ℓ with respect to the diagram (E_{max} and E_{min}). The reference correction establishes the angle of Γ_ℓ at the measurement plane. This is a simplified view of the measurement system.

Measurement sensitivity and resolution considerations can be enhanced by additional probes and modified techniques.

Figure 13 illustrates a system with probes located 90° apart. This system is inlcuded so that the reader might find some interesting solutions by developing techniques and calculations to obtain Γ_ℓ.

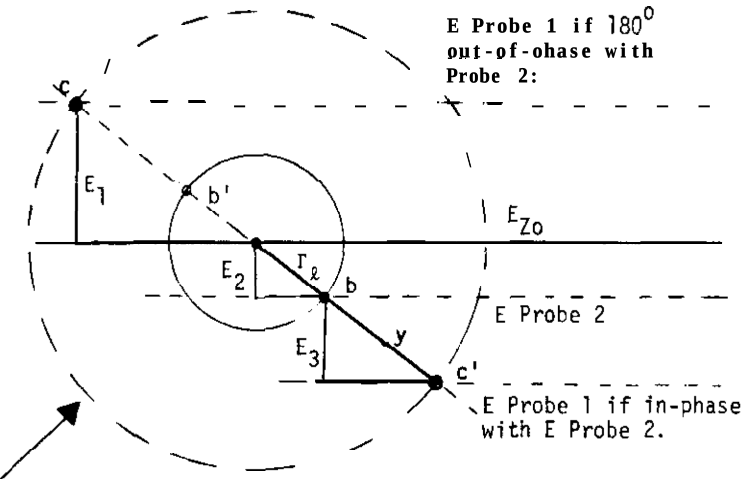


FIGURE 12 C. Magnified view of the NORMALIZER representation.

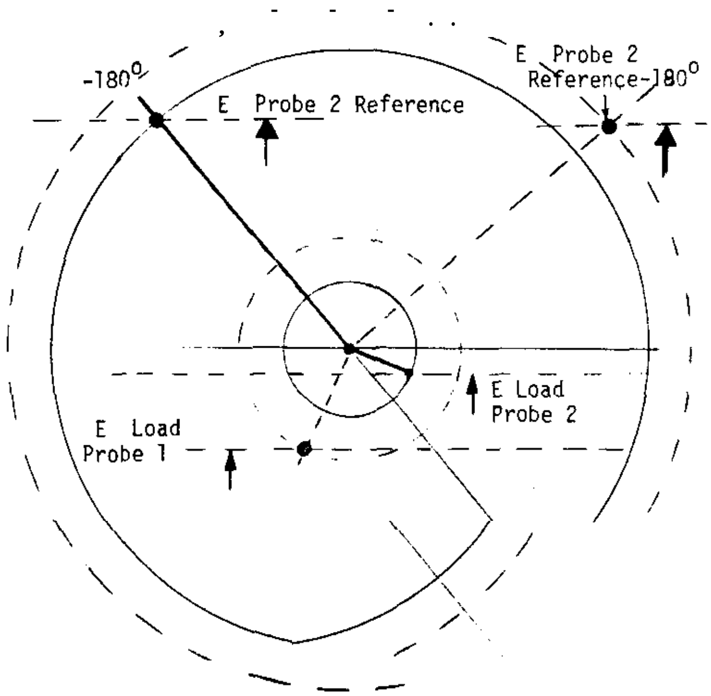


FIGURE 13. Two-probe system with probes located 90° apart. NORMALIZED representation.

Comments

The physical concepts dictate the path that the higher level methematics takes. They can be helpful when establishing the validity of conclusions.

The simplified versions of interesting system characteristics, shown in Figures 12 and 13, are merely thought provoking additions which, when coupled with previous discussions, may be of interest to developers of detection systems such as electronic slotted lines.

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RECENT INNOVATIONS IN DIRECT VOLTS CALIBRATOR DESIGN

Neil Faulkner and Walter Prue
John Fluke Manufacturing Company Inc.
Everett, Washington

ABSTRACT

High accuracy direct voltage calibration systems have traditionally been based upon precision resistive voltage dividers which are manually calibrated at frequent intervals to maintain the required resistance ratio. Due to resistance temperatiure coefficient, high accuracy is only attainable when the systems are used in a temperature controlled ambient, typically 23 +/-1 degree C.

This paper describes the design approach used in a direct voltage calibrator which does not require manual adjustment of resistor ratios to maintain accuracy. Internal calibration is an automated, microprocessor-controlled operation requiring no operator intervention. Resistance ratio determination and derivation of calibration constants is described. Design Of the environmental controls which enable the instrument to deliver rated accuracy of 4 ppm while operating in ambient temperatures +/- 5 degrees C from the calibration temperature will be discussed.

INTRODUCTION

High accuracy direct voltage calibration systems have, for many years, been based upon precision resistive voltage dividers which must be manually calibrated at frequent intervals to maintain required resistance ratio accuracy. Use of these systems was restricted to environmentally controlled areas due to the temperature coefficient of resistance of the voltage dividers. An additional restriction was manual operation only, because the high quality switching required for the resistance decades ruled out the use of relays.

To overcome these limitations an engineering project was initiated to develop a direct voltage calibrator suitable for calibration of high accuracy 6 1/2 and 71/2 digit voltmeters, that was remotely programmable and which could be operated over a reasonable temperature range. The instrument developed as a result of this project, the Fluke model 5440A, met all of the design objectives. It has a basic accuracy specification of 0.0004% (4ppm), is IEEE programmable, is calibrated completely without manual adjustments and can be used without degradation of specifications in ambient temperatures Of 15-30 degrees C. These objectives were met by building into the instrument a unique system for measurement of system and component errors and, with the calculation and control capabilities of the microprocessor, compensating these errors to near zero. This paper will examine in detail the automated measurements and procedures which accomplish this calibration process.

BLOCK DIAGRAM DESCRIPTION

A block diagram of the 54408 analog portion (See Fig. 1) consists of a very stable Voltage Reference (Vref), a Digital to Analog Converter (DAC) and a Power Amplifier (PA). The reference is a super stable constant voltage source O f approximately 13.2V. The reference polarity can be changed to negative by relays in series with the output.

The DAC (See Fig. 2) is the Pulse Width Modulated (PWM) type. An electronic switch at the input to the filter alternates between Vref and ground at a constant freq. Of 83 Hz. This signal is then filtered by a low pass filter to yield the do component. This dc voltage can be varied from OV to Vref by changing the duty cycle which is the ratio of the portion of the period the switch is connected to the reference to the total period. The duty cycle is controlled by the microprocessor.

The power amplifier, which is an inverting amplifier, is made up of two parts, a prs-amp which has very high gain and a current amplifier which supplies up to 25mA to the load (Fig 3). The gain of the PA is changed by switching in different feedback ratios to give different ranges. For the 10V range the gain is one, for the 20V range it is two, for the 250V range It is 25 and for the 1000V range it is 100. The 20V range is divided by a resistive divider with division ratios of 10 and 100 to give the 2V and 0.2V ranges respectively.

SYSTEM DESIGN

Calibrating the 5440A differs considerably from the technique used in previous calibrators. The most notable difference is that there are no potentiometers to be adjusted to trim resistors. Instead each part of the instrument is designed for extreme stability and linearity so that the output voltage can be related to the DAC duty cycle by a simple equation. Calibrating the instrument involves determining by measurements the constants used in this equation. Once determined the uP can calculate the proper DAC duty cycle required to give the desired output.

The performance of the DAC is the key element in producing a high accuracy calibrator. The most important characteristic is that it be very linear so that its output voltage vs duty cycle can be characterized by a straight line:

$$y = ax + b \qquad (1)$$

The equation for a straight line has only two constants to find, a and b. Once found, the operation of the DAC is fully characterized.

The uP controls the duty cycle through a count loaded into a counter in the DAC. This count will be called N1. With a count of zero the duty cycle is zero and the output of the DAC is zero. With a count of 24096 the duty cycle is 100% and the out put of the DAC is equal to Vref. The resolution of this circuit is equal to the change in output with a change of one count. This is equal to:

$$\text{Resolution} = \text{Vref}/24096 = 550\text{uV/Count} \qquad (2)$$

This is not sufficient resolution for a voltage calibrator so further division is necessary. Since switching speed places practical limits on minimum pulse width, other means must be found to obtain the required resolution. To this end a second switching circuit is employed (See Fig. 4), which uses the same switching frequency (83 Hz) and has the same range of counts, 0 to 24096 (the count will be celled N2), but has an input reference voltage which is attenuated from the 13.2 volts of the first switching circuit. The output of this second witching circuit is further attenuated before it is applied to the summing junction of the active filter. The overall attenuation, which will be termed RR (Ratio of Resolutions) is typically 7200. This makes the voltage resolution of the second switching circuit and thus the DAC:

$$\text{DAC Resolution} = 550\ \text{uv}/7200 = 76\ \text{nv/count} \qquad (3)$$

Exact value for RR is determined as a part of the instrument calibration.

The filter takes the pulses from the two switching circuits and filters out the dc component with a multiple pole filter with overall gain of negative one at do.

The DAC output also includes a" offset voltage (Vos). This offset comes from two sources within the DAC. First there is the offset voltage in the amplifier of the DAC active filter. Second there is a fixed offset introduced to improve linearity. The DAC is very linear down to N1=10 So to get good linearity down to zero volts it is required that the DAC be able to put out zero volt.? with N1=10. To accomplish this a fixed offset or bias of -5.5mV, equivalent to N1=10, is introduced at the input of the filter. This offset is obtained by inverting Vref, attenuating it to the proper level, and injecting it at the input of the filter (See Fig. 4).

The instrument outputs negative voltage by reversing the polarity of the reference. In the DAC this changes the fixed bias polarity but not the filter offset voltage. As a result the sum of these two offsets changes when the polarity is reversed. This results in two values for the offset, one for positive polarity and one for negative polarity.

The output of the DAC is given by the equation:

$$\text{DAC Out} = (G_F)\{(\text{Vref})(DC_1) + (\text{Vref}/RR)(DC_2) - (Vos_{dp})\} \qquad (4)$$

Where: Vref=Reference Voltage (13.2V)

DC_1=Duty Cycle of the 1st Switching Circuit

DC_2=Duty Cycle of the 2nd Switching Circuit

G =Gain of the DAC Filter(-1)
R&Attenuation Factor of 2nd Switching Circuit

Vos_{dp}=DAC Offset voltage where Polarity is positive or negative

Now relating duty cycle to N1 and N2:

$$DC_1 = N1/24096 \qquad (5)$$

$$DC_2 = N2/24096 \qquad (6)$$

Substituting (5) and (6) into (4) end factoring gives:

$$\text{DAC Vout} = (G_F)\{(\text{Vref}/24096)(N1+N2/RR) - (Vos_{dp})\} \qquad (7)$$

Relating equation (7) to equation (1) the constant $(\text{Vref}/24096)(G_F)$ is the value for a. The variable (N1+N2/RR) is the value of x and the offset voltage $(-Vos_{dp})$ is the value for b.

Following the DAC is the Power Amplifier whose gain can be programmed by the uP to give different ranges. This amplifier also has an offset voltage of its own which is slightly different for each range. Following the PA is a Divider which is used only on the 0.2V and 2V ranges. It alters the overall gain of the PA when used but doesn't add any offset voltage of its own. The equation for the output of the PA is:

$$\text{PA Vout} = (G_{PAx})\{(\text{PA Vin}) + (Vos_{ax})\} \qquad (8)$$

Where: PA Vout=PA output voltage

x=Range(0.2V,2V,10V,20V,250V and 1KV)

G_{PAx}=Gain of the Power Amplifier and Divider (when used) on range x

PA Vin=PA input voltage

Vos_{ax} = PA offset voltage on range x

The input to the PA is the output of the DAC so equation (7) can be substituted for (PA Yin) in equation (8). The resulting equation is:

$$PA\ Vout=(G_{PAx})(G_F)(Vref/24096)(N1+N2/RR) - (G_{PAx})(G_F)(Vos_{dp}) + (G_{PAx})(Vos_{ax}) \qquad (9)$$

The output Of the PA is connected to the instrument output terminals so the above equation is equal to the output voltage of the 5440A. Making some substitutions this equation becomes:

$$5440A\ Vout=K_x(N1+N2/RR)-Vos_{xp} \qquad (10)$$

Where: 5440A Vout=5440A output voltage

x=Range(0.2V,2V,10V,20V,250V and 1KV)

$$K_x=(G_{PAx})(G_F)(Vref/24096)$$

$$Vos_{xp}=(G_{PAx})(G_F)(Vos_{dp}) - (G_{PAx})(Vos_{ax})$$

Equation (10) also has the same form as equation (1) where:

y=5440A Vout
$a=K_x$
x=(N1+N2/RR)
$b=-Vos_{xp}$

CALIBRATION PROCESSES

To calibrate the 54401 it is necessary only to determine the values for K_x, Vos_{xp} and RR. Since the output is characterised by a straight line, finding the values for K_x end Vos_{xp} only requires finding two points on that line. Since the DAC is linear down to OV it is one of the two points used. To find this point the instrument goes thru en auto zero process whereby it is zeroed, under program control, on each range and both polarities. It is during this process that the value for RR is determined. Since RR is the ratio Of resolutions, its value is equal to the "umber of N2 counts that changes the output by the same amount as one Nl count. After the instrument has been set to OV on the 10V range N1 is decremented by one count and N2 incremented until the output is again OV. The number of added counts of N2 required to reach zero is equal to RR.

The hardware used to do this auto zero involves a low noise amplifier and low thermal EMF relay connected to the 5440A output (See Fig. 5).
The 5440A contains a 12 bit plus sign bit (13 total *bits)* A/D which is under uP control. Its input can be switched to various points within the 5440A circuitry by means of multiplexers. One of these points is the output of the low noise amplifier. The auto zero process first measures the amplifier output with the input connected to Sense LO which places a short circuit or zero volts on the input. The output reading is not normally zero as the amplifier has a" offset voltage of <=250uV. The voltage that is read is stored by the uP. The output of the 54401 is set to zero by the uP according to values Of K_x, Vos_{xp} and RR it has previously stored in memory. The relay is then closed and a new reading taken. The difference between these two readings 'divided by the gain of the amplifier equals the amount the 54408 is off zero. If the 5440A output is off too far the DAC output is incremented or decremented by a programmed amount in the direction to achieve zero. Another set of readings is taken and the process repeated until the difference from zero is within prescribed limits. The program then stores the Nl and N2 count required for zero and goes on to the next range.

The next step is to find the second point on the straight line. The best point would be one as near Vref es possible but because of the excellent linearity of the DAC a point half Way up the line can be used with satisfactory results. This Process requires external equipment and operator intervention so is called External Calibration (EXT CAL).

Figure 6 shows the connection of external equipment used to calibrate the 10" and 20V ranges. A null detector with uV resolution such es a Fluke 845A is connected between the 54408 HI output and the HI output of a Precision 10" voltage standard like the Fluke 732A.

The operator first connects the external equipment the" enters the exact voltage of the voltage standard through the 54406 keyboard. If the Fluke 7321 is used the standard voltage is 10". The 544011 then outputs the same voltage as the standard using the values for constants currently in memory. The null detector then indicates bow much the 54401 output differs from that of the voltage standard. The operator then increments or decrements the 5440A output until the null detector reads OV. At that point the 54408 is putting out the same voltage es the voltage standard. The "ENTER" button is pressed and the values for N1 and N2 used to get this voltage are stored in memory.

To calibrate the other ranges a precision voltage divider such as the Fluke 752A is required. This divider is used to divide 100V on the 250V range by 10 and 1000V on the 1000V range by 100 to get 10V which is again compared to the 10V Prom the 732A standard (See Fig. 7).

To calibrate tbe 2V range the 752A divides the 10V from the 732A by 10 to get 1V which is compared to the 54401 output. For the 0.2V range the 752A divides the 10V by 100 to get 0.1V (See Fig. 8).

When all six ranges have been calibrated with the external equipment the program then calculates the new values of K and Vos. It does this by using the values of N1,N2 and RR it has stored in memory from the auto-zero process and EXT CAL. A value of K for each of the six ranges is calculated using the following equation:

$$K_x=Std\ V_x/\{(N1s_x-N1z_{xp})+(N2s_x-N2z_{xp})/RR)\} \qquad (11)$$

Where: x=Range (0.2V, 2V, 10V, 20V, 250V, and 1000V)

$StdV_x$=Voltage Standard Voltage used on range x.

N1s and N2s=N1 and N2 used by the 54488 to output a voltage equal to the standard on range x.

$N1z_{xp}$ and N2z=N1 and N2 used by the 5440A to &put zero volts on positive polarity and range x.

There are eight values for Vos, one for each polarity, for the 10V through 1000V ranges. The Vos values for the 0.2V and 2V ranges when scaled by 10 and 100 respectively so nearly equal the 20V range values that the 20V range values are used without further correction. Tbe equations used to calculate vos are:

$$Vos_{xp}=K_x(N1z_{xp}+N2z_{xp}/RR) \qquad (12)$$

Where: Vos_{xp}=Offset Voltage for Positive or Negative Polarity on Range x

x=Range (10V, 20V, 250V, and 1000V).

K_x=Value of K for range x.

Nlz and $N2z_{xp}$=N1 and N2 used by the 544w to output zero volts on positive or negative polarity and range x.

Once all the values of K and Vos are calculated they and RR are stored in non-volatile memory so they will not be lost when power is turned off. This completes the calibration of the 5440A, a process normally done every 30 days.

IMPROVING PERFORMANCE WITH INTERNAL CALIBRATION

To improve the 54408 accuracy between the 30 day calibrations Internal Calibration (INT CAL) is normally run daily. It first goes through the auto zero process on the 10V through 1000V ranges and finds the value for RR as already described. From this information any change in the values of Vos can be corrected using the new values of N1z sod N2z.

The value of K can also change if the value of Vref, DAC gain and/or PA gain changes. A second part of INT CAL switches the instrument into a special configuration which allows measurement of any shift in the value of K due to a shift in DAC or PA gain and thus determines correction for the shift. Any shift in the value of Vref can only be corrected for by EXT CAL.

The special configuration used during INT CAL to determine the gain shift in the 10V range is shown in Fig. 9. To acheive this configuration:

1. In the DAC the reference is connected directly to the filter input. This is accomplished by setting the first switching circuit to 100% duty cycle and the second switching circuit to 0% duty cycle.

2.1" the DAC the bias supply is disconnected.

3. In the PA the feedback resistance which connects between the PA output and the Pre-Amp input is disconnected from the PA output and connected to the reference.

4. The Pre-Amp is disconnected from the current amplifier and configured into a "on-inverting amplifier with a gain of approx. 600. Its output is connected to the A/D through a ❑ ultiplerer.

The gain of the DAC and the PA are set by resistors and this special configuration places these resistors in a type of bridge configuration so that small shifts in resistor ratios and thus the gain can be accurately measured. Since the resistors are not exactly equal and there is offset voltage in the DAC filter amplifier, the voltage at the input to the Pre-Amp is not normally zero but is <1.2mV. Through the Pre-Amp, with its gain and offset voltage the maximum voltage at the input to the A/D is <1V.

The voltage at the input of the A/D is a' function Of offset Voltage of the DAC filter and the Pre-Amp as well as resistor ratio. To overcome this problem the program takes two measurements and the" subtracts one from the other. The first measurement is taken with the connections es show" in Fig. 10 and the second take" after the polarity of the reference is reversed. When the second reading is subtracted from the first the offset voltages drop out of the calculation leaving only the effect of resistor ratios. The difference of the two ❑ eeeuraments varies in direct proportion to the total shift in gain of the DAC end PA.

When EXT CAL is performed, the value of K is accurately set and stored in memory. Since INT CAL is always run prior to EXT CAL a set of readings for the instrument gel" shift are take" and stored. The next time INT CAL is run a new set of readings is taken and their difference compared to those stored when BIT CAL was r"". Any change in the differences is proportional to any gain shift so the program uses the amount of change to determine how much to change the value of K using the equation:

$$\Delta K_{10}=((V1-V2)old-(V1-V2)new)/24096 \qquad (13)$$

Where: Vl and V2 are the voltages at the input of the Pre-Amp with a positive Vref and a negative Vref respectively for the 10V range.

The "old" values are those in memory from the last time INT CAL was run.

The "new" values are the current readings.

As implemented in the 5440A a change in gain of 0.1ppm can be determined. Note that this technique cannot measure the actual gain accurately but only small shifts in gain. As mentioned earlier it does not correct for drifts in Vref but any drift in Vref does "ot affect the accuracy of determining the gain shift.

This same technique can be used to determine the gain shift of the 20V, 250V and 1000V ranges. Tbe feedback resistance used on these ranges is 40K, 500K and 2M respectively so none of them can be compared directly with the 20K reference resistor. This Problem is solved on the 20V range by splitting the 40K into two 20K's. One of the 20K's is the one used for the 10V range. The other 20K is then switched into the bridge and compared Separately. The shift in K due to this 20K is calculated and added to the shift already calculated for the 10V range and this becomes the shift for the 20V range. The equation for the shift in K for the 20V range is:

$$\Delta K_{20}=\Delta K_{10}+\{(V1-V2)old-(V1-V2)new\}/24096 \quad (14)$$

Where: V1 and “2 are for the 20V range.

The 250V range and the 1000V range “se the same ten 200K resistors configured differently for each range (See Fig. 10). For INT CAL all ten are connected in parallel to give 20K which is switched into the comparison bridge. Again a set of readings is taken and their difference calculated. The shift in gain using the resistors in parallel can be related to the shift in K for the 250V range and 1KV range where the resistors are used in a different configuration. The shift is simply multiplied by the gain for that range as can be seen in the following equations for the shift in K:

$$AK_{250}=25\{(V1-V2)old-(V1-V2)new\}/24096 \quad (15)$$

$$AK_{1KV}=100\{(V1-V2)old-(V1-V2)new\}/24096 \quad (16)$$

Where: V1 and V2 are the bridge readings taken for the ten 200K resistors in parallel.

The shift in the values of K for the 0.2V and 2V ranges cannot be determined by INT CAL. Since these ranges are obtained by dividing down the 20V range, which is corrected by INT CAL, only the drift in the divider ratios degrades the accuracy of the values of K. These ratios are stable enough as to only require calibration every 30 days by EXT CAL.

ENVIRONMENTAL CONTROLS

The internal and external calibration procedures are designed to correct for long term (greater than 24 hours) changes which take place in the instrument components and circuitry. To ensure short term stability it is important that sensitive circuit components be maintained in a very stable environment. The 5440A package design includes three temperature controlled component ovens. The first oven encloses the solid-state reference components and sensitive DAC components, the second contains the pre-amplifier and the third encloses the Power Amplifier range resistors. The ovens are made by surrounding a section of the printed circuit board with thick aluminum blocks which contain heater resistors. This assembly is then covered with a foam insulation layer and a protective cover. The oven temperature is proportionally controlled using a stable glass bead thermistor sensing element to maintain a temperature of about 50 degrees C. A second thermistor in each oven is used to monitor temperature for instrument self-test data.

In addition to temperature stabilization, sensitive components are selected and matched for very low temperature coefficient. The direct result of this selection and temperature control is the ability of the instrument to operate at full rated accuracy specifications over a wide range of ambient temperature.

PERFORMANCE

The internal calibration procedure described is initiated by pressing front panel keys and once started is a completely automatic process taking about 5 minutes. It is normally done once every 24 hours but may be initiated at any time for example, to correct for large changes in ambient temperature. Internal calibration corrects for all component shifts except the reference element and the resistive dividers for the 2.0 and 0.2 volt ranges. External calibration, normally performed at 30 day intervals, corrects for shift in the reference and the low voltage divider. It requires use of a null detector, an external reference voltage and a voltage divider. It requires about 15 minutes to perform and involves the operator through prompting by the alpha-numeric display. No mechanical adjustments are required; only incrementing or decrementing output voltage from the front panel.

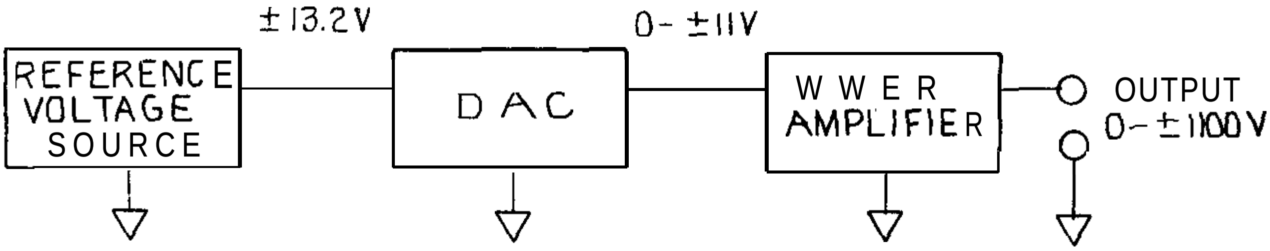


FIG. 1 SIMPLIFIED BLOCK DIAGRAM, ANALOG SECTION

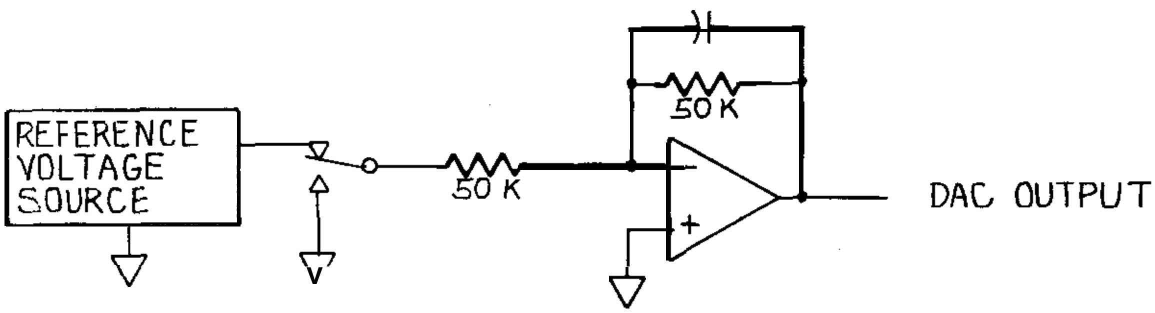


FIG. 2 SIMPLIFIED DIAGRAM OF PWM DAC

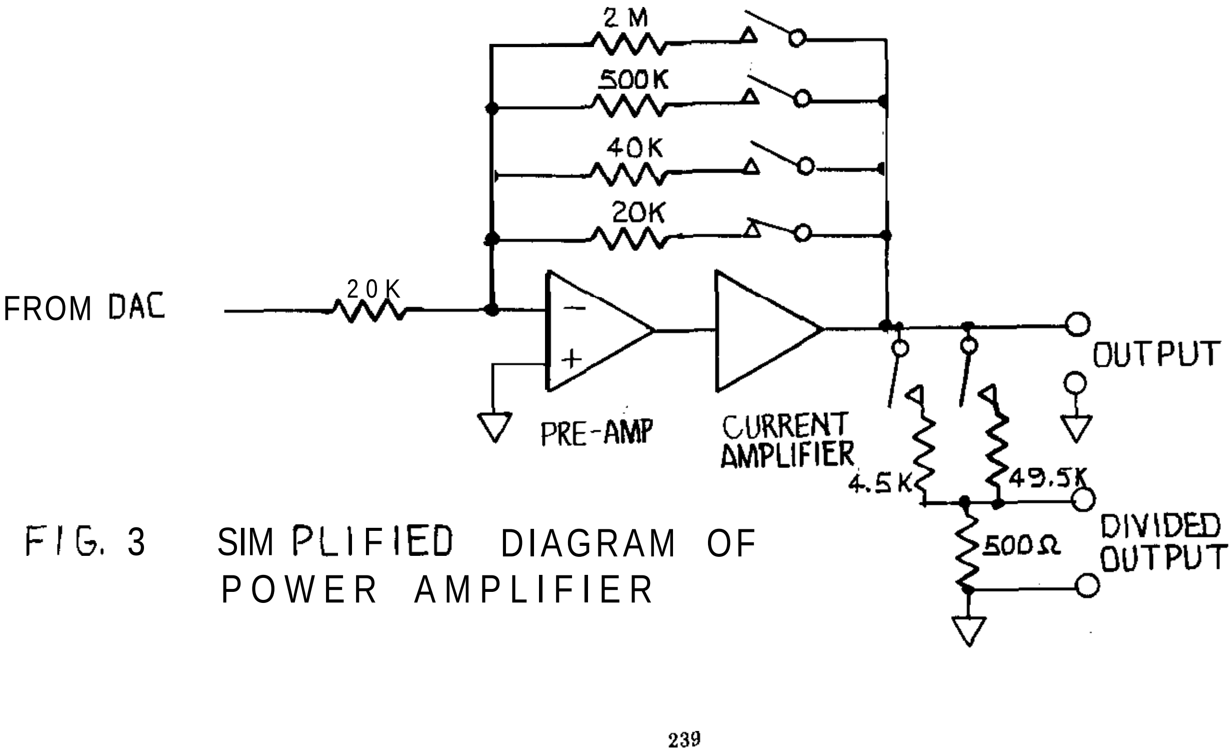


FIG. 3 SIMPLIFIED DIAGRAM OF POWER AMPLIFIER

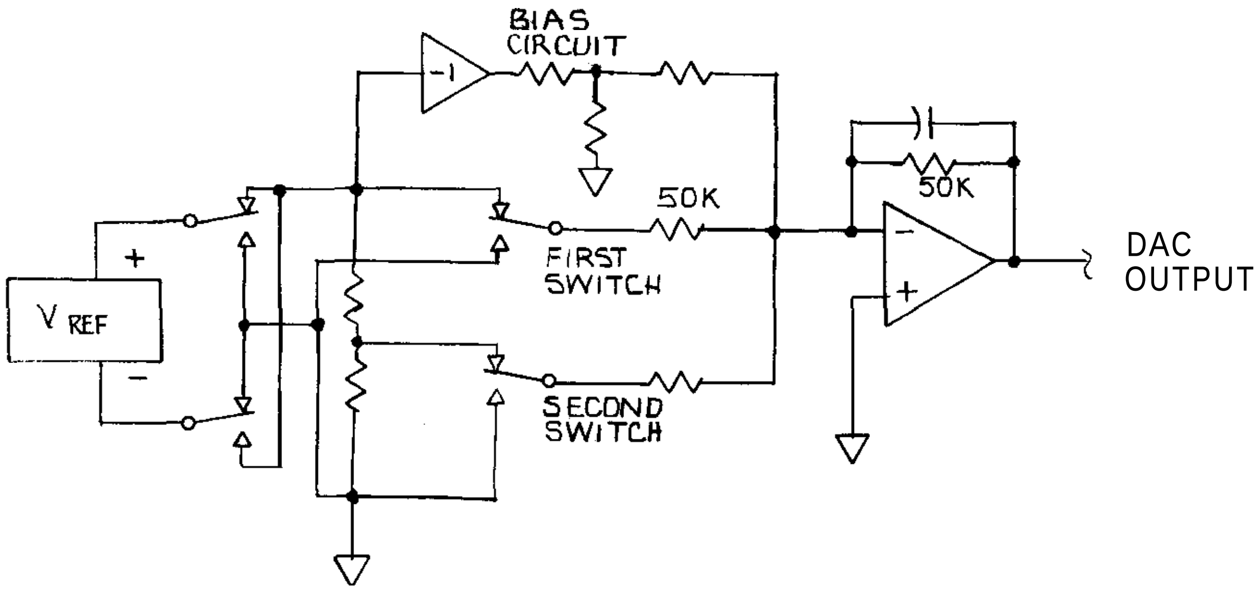


FIG. 4 DUAL SWITCHING DAC

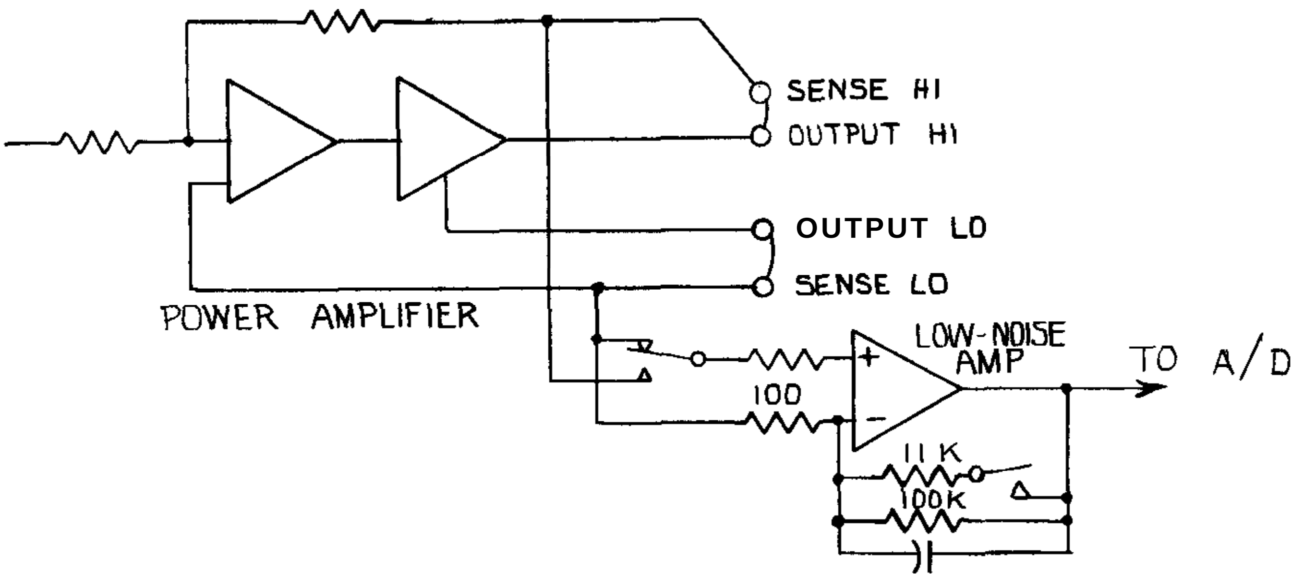


FIG. 5 AUTO -ZERO CIRCUIT

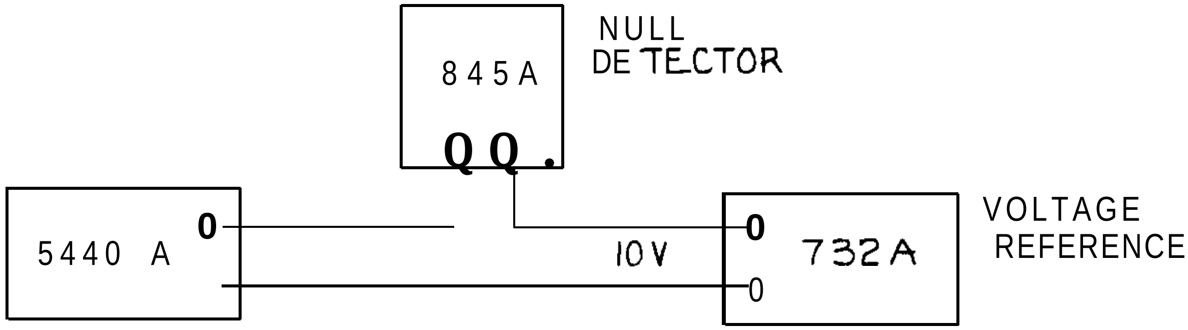


FIG. 6. EXTERNAL CALIBRATION OF THE
10 V. AND 20V. RANGES

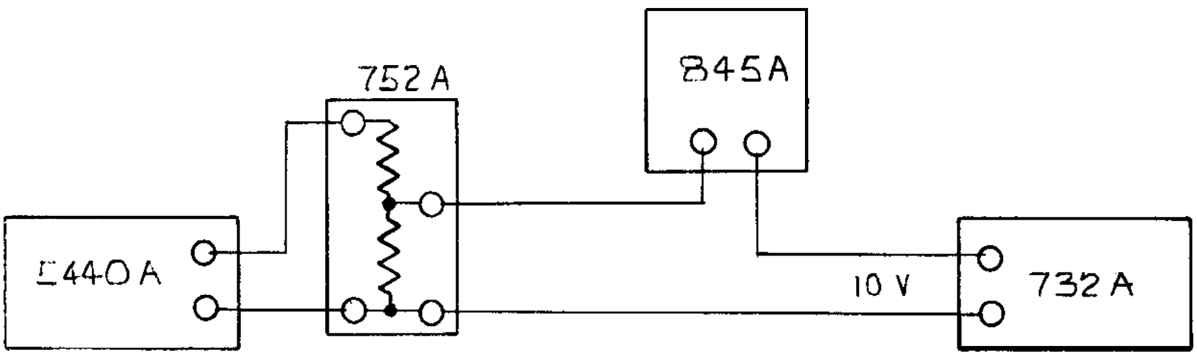


FIG. 7. EXTERNAL CALIBRATION OF THE
250 V. AND 1000V. RANGES

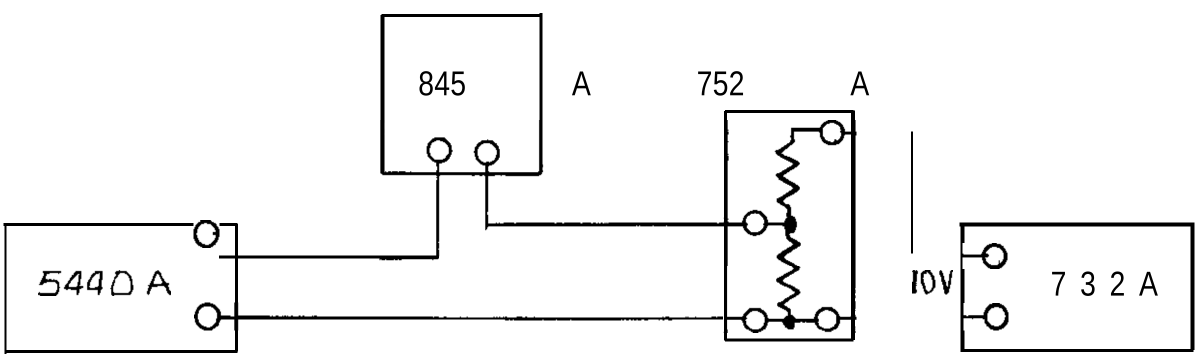


FIG. 8. EXTERNAL CALIBRATION OF THE
0.2 V. AND 2.0 V. RANGES

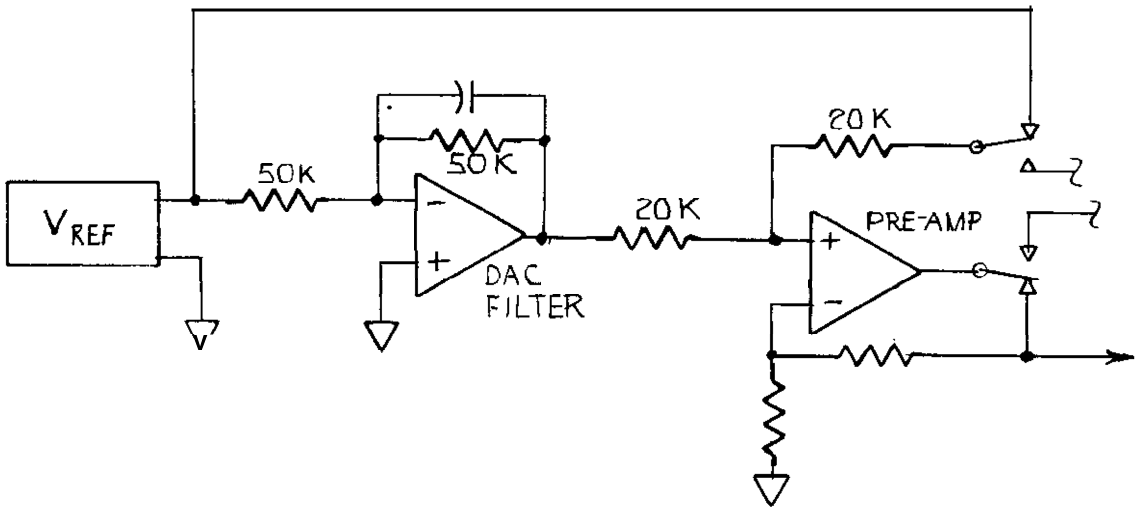


FIG. 9. INTERNAL CALIBRATION, GAIN SHIFT MEASUREMENT CONFIGURATION

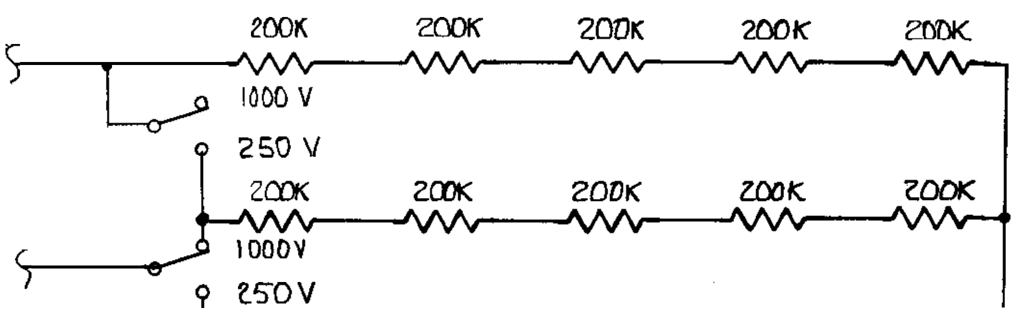


FIG. 10. CONFIGURATION OF TEN 200K RESISTORS FOR THE 250V AND 1000V RANGES.

Inventory Data Management Using A Microcomputer

Paul Baldock
Project Manager
Calibration Products
John Fluke Mfg. Co., Inc.
PO BOX C9090,
Everett, WA 98206

ABSTRACT

Traditionally, inventory data management systems have required large high-speed computers for their implementation. The limited storage and processing capabilities of microcomputers have precluded their use from extensive data handling.

Thin paper presents a technique where a large data base can be reduced to its common elements and thus minimize storage requirements. The technique is illustrated by implementation of a 'Calibration History Management System', where approximately 2,000 instruments, each with 10 detailed historical records, can be stored and manipulated using a single 200K Byte flexible diskette.

The paper also emphasizes the advantages of being able to reconfigure the data structure easily, so as to expand its utility to other data bases.

INTRODUCTION

Most major businesses have data management systems which are used to control such things as payroll, order processing, parts inventory and manufacturing processes. These computers tend to be large, expensive mainframes with extensive memories and often timeshared for a multiuser environment. Systems such as these are usally managed and supported by departments of computer scientists, engineers, and data processing personnel. This paper is concerned with implementing a data management system for Calibration Records, and independent of the sort of computer facility just described that has traditionally been used.

Calibration Records Management is generally required for instrument recall, inventory control, and calibration report generation. Often a data base must cope with many thousands of different instruments, each with its own batch of historical data. This requirement for a large data base has, in the past, precluded the systems implementation on the smaller 'controllers' or microcomputers. I" addition, the limitations of the microcomputer has put practical limitations on the amount of data that can be manipulated quickly.

Another limitation of using an in-house large data Processing system to store calibration records is lack of versatility when changes in format are required. This may be due to the complexity of structure of these systems or just being able to gain the time of one of its support personnel, to implement the new requirements for what is probably one of the lower priority functions. With these limitations in view, the objective set was to design a data management system, primarily orientated towards calibration records. This would store sufficient information for most requirements, have considerable versatility in restructuring the data base, or the "se of the data base and, of course, include the function of data sorting in a resonable period.

SOME STANDARD TYPES OF DATA STRUCTURE

Before examining the particular implementation of the Calibration History Managment System, types of data bases used in other systems will be reviewed and compared.

A Linear Data Base

A linear data base is one where each individual item in that data base has its own dedicated entry. Each entry is self contained in that it holds the entire information required for that entry. A simple 2 dimensional matrix is a" example of the linear data base.

Material Type	Color	Density lbs/ci	Stock Tonnes
3G	GREY	.08	1000
3G	GREY	1.0	1100
3G	BLACK	.08	2000
3G	BLACK	1.0	1105
4G	GREY	.09	875
4G	BLACK	.09	2000

Number of data points: 24

Figure 1:
Linear Representation of 'Material' Data Base

The following represents a typical search algorithm to find all stock with densisty of .08 lbs/ci in the data base illustrated by Figure 1:

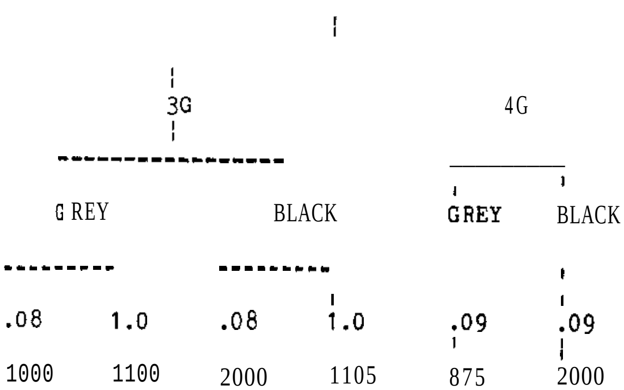
```
SEARCH COLUMN HEADER FOR 'DENSITY'
REPEAT
     READ ELEMENT IN ROW OF SELECTED COLUMN
     IF .08 FOUND
          PRINT COMPLETE ROW
     ENDIF
     INCREMENT TO NEXT ROW
UNTIL ALL ROWS READ
```

As is illustrated above, the search algorithm is short and fast. All that is necessary is for the program to identify the correct element data (.08), then all the required information is included in that row and available for printing.

The big disadvantage of this scheme is the large amount of storage required. Each individual item in stock has its own row or entry. No effort is made to link common elements and reduce space.

A Hierarchical Data Base

An hierarchical data base is one where data is grouped like a tree with branches interconnecting elements. For instance, if an element has multiple, exclusive attributes, then these attributes are branched off from that element.



Number of data points: 18

Figure 2:
Hierarchical Representation of 'Material' Data Base

The following represents a typical search algorithm to find all stock with density of .08 lbs/ci in the data base illustrated by Figure 2:

```
REPEAT
     READ MATERIAL TYPE FROM LEFT TO RIGHT
     IF MATERIAL TYPE OK
          REMEMBER MATERIAL TYPE
          REPEAT
               READ COLOR LEFT TO RIGHT
               IF COLOR OK
                    REMEMBER COLOR
                    REPEAT
                         READ DENSITY LEFT TO RIGHT
                         IF DENSITY .08
                              PRINT COMPLETE
                              INFORMATION
                         ENDIF
                    UNTIL ALL DENSITY CHECKED
               ENDIF
          UNTIL ALL COLORS CBECKED
     ENDIF
UNTIL ALL TYPES CHECKED
```

(Note, in the above example all material types and colors are OK.)

The example above illustrates fast searching on the root and upper level branches, but when searching for a lower level requirement, such as the density having to be .08, it has to go through many time consuming loops.

Data storage is more economical than the linear example earlier. However, there is still duplication of data. For instance, colors occur in two locations.

A Network Data Base

A network data base is made up of elements, whose relationship is indicated by pointers between the elements. This permits non-hierarchical relationships. For example, more than one material can point to the same color.

	Quantity	Type	Color	Density
a	1000			
b	1100	3G	GREY	.08
c	2000			.09
d	1105	4G	BLACK	1.0
e	875			
f	2000			

Number of data points: 13

Figure 3:
Network Representation of 'Material' Data Base

In Figure 3 the reference element, or element from which all pointers eminate, is represented by the 'Quantity'. The following represents a typical search algorithm to find all stock with density of .08 lbs/ci:

```
REPEAT
     READ MATERIAL POINTERS
     STORE ALL MATERIAL POINTERS
     READ DENSITY TO WHICH MATERIAL POINTS
     IF DENSISTY .08
          PRINT COMPLETE INFORMATION USING
          POINTERS FROM MATERIAL
     ENDIF
     INCREMENT TO NEXT MATERIAL
UNTIL ALL MATERIALS READ
```

The example above has a short search algorithm, although it is likely tc be slow because of the many accesses to the data base, and the probable quasi-random positioning of that data.

All duplicate elements have been eliminated by the network method minimizing the space for data, but it is now necessary to allocate space for the pointers. One enhancement that could be made tc this technique is tc include the ability for backwards searching. For example 'GREY' would have backwards pointers tc '1000', '1100', and '875'. Search for all GREY materials would then be accomplished by locking in the color location for GREY and locating the materials to which it points. I" essence, each element becomes the source from which pointers eminate. In this case a trade off would be made between extra pointer storage space for less element storage space.

CALIBRATION HISTORY MANAGEMENT APPLICATION

The following sections deal with implementing a Calibration History Management System on a FLUKE 1720A Microcomputer. The 1720A has 64K Bytes of RAN, 256K Bytes E-Disk™, and a 199K Byte Minifloppy. These sections will concentrate on areas associated with the data base definition, modification and manipulation.

Data Base Specifications

Calibration records are split into 'Instrument Data' and 'History Data'. Instrument data describes information particular tc an instrument that does not vary with time. History data describes information about a particular event or calibration pertaining to an instrument. For a single instrument there may be many History records.

The stored Instrument data requirements are as follows:

Title	Default size
Manufacturer/ Model No*	56 Characters
Location Name*	"
Remark*	"
Calibration Interval	< 256 weeks
Serial Number	16 Characters
Date Next Calibration	< 32768 days

The stored History data requirements are as follows:

Title	Default size
Operator Name*	16 Characters
UUT Code*	"
System Type	< 164
Result	Pass or Fail
No. of Adjustments	< 256
Date of Calibration	< 65536 days
Calibration Time	< 65536 minutes

The disk allocation requirements are as follows:

Each Instrument record will have up to 10 History records associated with it. This number will be flexible, and be used to calculate the maximum number of instruments that can be stored an a disk.

Those records marked with the asterisk (*) are to have flexible size in that their length may be adjusted in multiples of 8 characters. In addition, provision is made for a 'spare string entry' to be available in both the Instrument and History records. This flexibility allows each user cf the Calibration History Management System to optimize it for his own particular need. If the user requires more Histories per Instrument but retain the same number of Instrument per disk, he can choose to reduce the length of some other data field, and swap the space.

Data Base Structure Utilized

The data structure utilized is a combination of a Linear and Network scheme. Figure 4 illustrates this scheme.

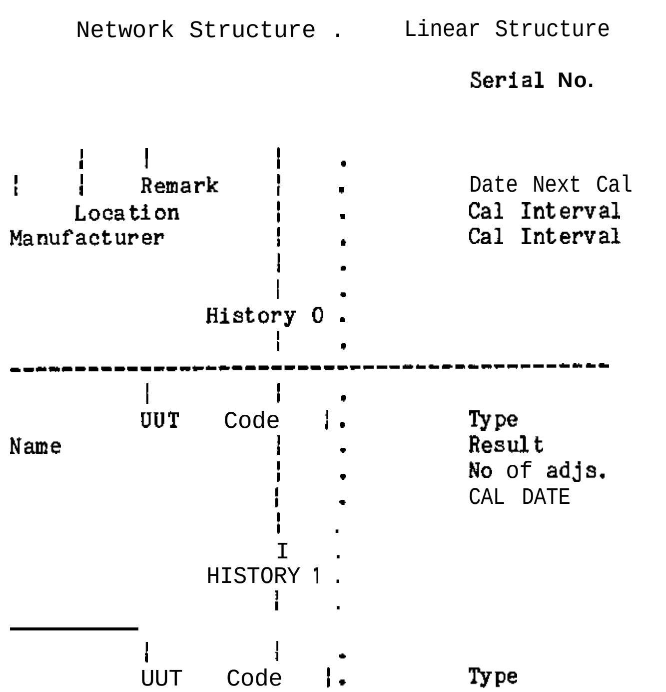


Figure 4:
Combined Linear and Network Data Base Structure

The right hand side of Figure 4 represent a Linear structure where information is contained sequentially with its reference point. In this case, the reference point is the Serial Number or History Record. The left hand side of Figure 4 represents a Network Structure, *these being elements* that are pointed to from a reference point. It can be see" that there are, in fact, two levels of Network structure. The first level is the History reference point being pointed to by the Serial Number location, and the second level, the History reference painting to other elements.

The elements considered part of the Network structure are those elements that are common to more than one Instrument or History. Elements that are particular to an individual Instrument or History are considered pert of the Linear structure. Network elements are pointed to by variable stored within the Linear structure. Figure 5 attached shows this in more detail. This is a reprint from the Fluke 7400 Calibration History Management Programming Manual.

Refering to Figure 5, 'HIST.BIN' is the file where most of the data is stored. For convenience in searching, 'Date Next Calibration' is stored in a separate file called 'HIST.DAT'. HIST.DAT also contains pointers to the first record of the various data fields of HIST.BIN. This will be delt with in more detail later in the section celled 'Reconfiguring the Data Base'.

Instrument strings are contained in a block immediately prior to the History Strings. The Serial Number and Cal Interval-are contained directly in the Instruments string. the rest of the string consists of pointers beck into HIST.BIN. Some of these pointers are absolute. For example, the number stored in the first 2 bytes of the instrument string points directly to the location containing the Manufacturer/Model. Some of the pointers are relative. For example the 6th byte contains the offset for the Remark String relative to the first possible Remark String in HIST.BIN. Using relative pointers reduces the "umber of bytes necessary to store their index.

History strings are stored in HIST.BIN in a location related to the Instrument of which they are history. The relative formula is included in Figure 5. Like the instrument string, history strings directly contain some information, and other fields, such es the Operator Name end "UT Code, are located by pointers back into HIST.DAT.

The combination of direct data access (linear structure) end data access through pointers (network structure), is designed to provide the optimum solution of fast data access and high densisty storage.

Software Structure Utilized

The Calibration History Management software hierarchy is illustrated in Figure 6, attached. This is a reprint from the Fluke 7400 Calibration History Programming Manual. Each block of Figure 6 represents an individual program. The programs are linked via a common data file which will be described further in the next section. Each of the general program functions are described es follows:

System Directory Program

This directory program is the central logic point of the management system. MGTPRT is entered on a power fail, Initial system boot, and between each major function of the system. This program has the ability to define a password in order to protect history data integrity.

History Update Program

Before history data can be stored about a particualar instrument, that instrument has to be defined on a data disk. MGTUDF provides that utility es well as the ability to modify existing Instrument data.

Report Printout Program

The purpose of a Calibration History Management System generally culminates in the printing of some sort of report, be it for instruments recall or some other facility. MGTPRT provides the printout utility.

Report *Definition* Program

Reports printed from a Management System are usually selective in that, in most instances it is not required to print out the total data base. MGTDRT allows for the generation of report definitions. These definitions restrict the information that is to be included in a report.

Results Download Program

The particular Calibration History Management System being described allows data to be entered either by hand or automatically downloaded from the FLUKE 7400 Series Calibration Systems. MGTUD1 interfaces the history data base with the 7400 Calibration System's results data.

system Configuration Program

The Calibration History Management System data format is flexible. This data format is defined in MGTCFG, and is described in detail in the section following called 'Reconfiguring the Data Base'.

History Disk Initialization

The history data base is stored on minifloppy diskettes. The data Format is flexible as defined by MGTCFG. The disks have to *be* configured in this defined Format. MGTINI initializes a disk based on the format defined in MGTCFG.

Reconfiguring the Data Base

The Calibration History Management Software is specifically structured so that the data base format can be customized and modified easily. The configurator program MGTCFG sets up the various fields of data, their size and their quantity, and so for many applications this is the only program that need be changed.

Figure 5, attached, shows in detail the construction of the data base. The data file HIST.DAT contains the variables that describe the size and positioning of the various data fields and is contained along with the data base on the disk. These variables are equivalent to a set of variables which are defined in the program MGTCFG. The variables as defined by the configurator program are copied to a History disk when it is initialized. This has the effect of allowing each disk to contain the decriptio" about its oH" data format, allowing the same Management System to manipulate disks with different data formats.

A complete description of the variables that define the position and size of the History data base are included in Figure 7, attached. Figure 8, attached, is a" extraction from the program MGTCFG where these variables are defined. By changing the values of the variables, the data format can be redefined. Consider the simple case where it is wished to add 300 spare instrument strings of length 32 characters. It is only necessary to change CO(3) to 300 and CO(4) to 32. I" addition only 5 History records per Instrument may be needed, so change CO(30) to 5. The program MGTCFG is the" RUN and all relevant pointers recalculated. I" this case the "umber of instruments that can be stored on a disk has changed from 1677 to 2576.

If data is to be archived according to the modified data base definition, the" it must be stored on a disk initialized with that definition. This is accomplished by RUNNING MGTINI on the new disk.

The Calibration History Management System in Use

The 1400 Calibration History Management System is a me"" drive" system capable of storing data, either entered manually or from a" automatic calibration station. This data can the" be manipulated to produce reports.

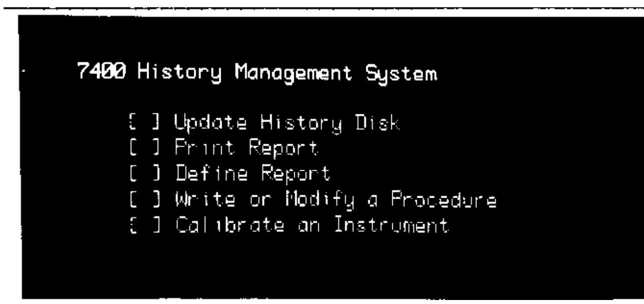


Figure 9:
Main System Menu

Figure 9 shows the selection of the major system functions. Pressing the 'Update History Disk' selection allows for adding results to a" existing data disk, modifying a" existing data disk, or initializing a data disk. This is depicted in Figure 10.

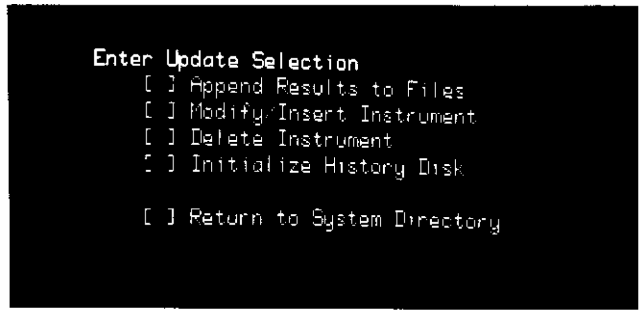


Figure 10:
Data Disk Update Menu

Before History data can be added to a" Instrument file that instrument file has to be created on the data disk. Two methods are available to perform this function. One method is to extract the information automatically from the results as they are being entered, and then add any additional instrument data later; the second is to manually enter the Instrument data prior to down loading any History data.

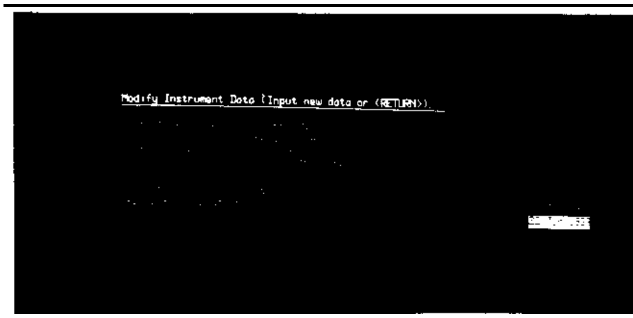


Figure 11:
Entering Instrument Data

Figure 11 is a" example of entering or modifying Instrument data. The reverse video block highlights the current data field being entered. This information may be compared with the data structure illustrated in Figure 5.

The type of information that is to be included in that report must be defined before a report can be printed. This selection is made in the me"" of Figure 12.

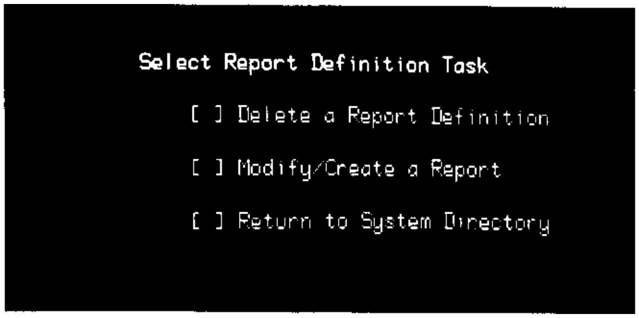


Figure 12:
Report Definition Menu

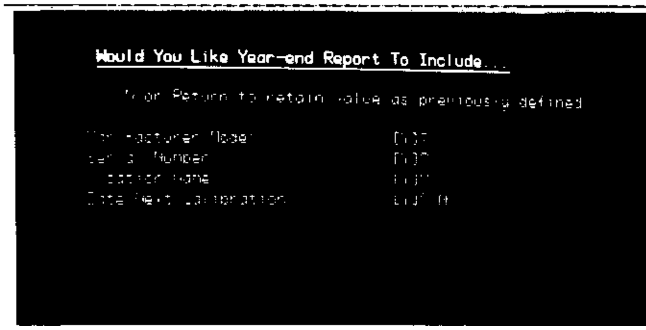


Figure 13:
Report Definition Entry

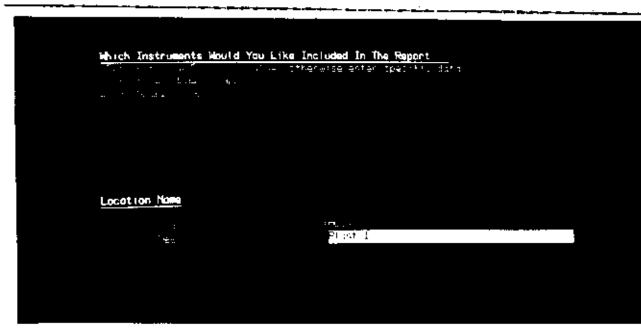


Figure 14:
Report. Definition

Figure 13 shows selecting the fields that are to be included. Figure 14 shows defining the report Parameters by which the Particular Instruments and Histories will be chosen. The Calibration History Management System under discussion allows for the definition and storing of UP to 32 different report formats.

The main menu, illustrated in Figure 11, allows the user to choose the option of printing a report. These reports may be Printed on either the microcomputer CRT, or a printer. Figure 15 shows this choice.

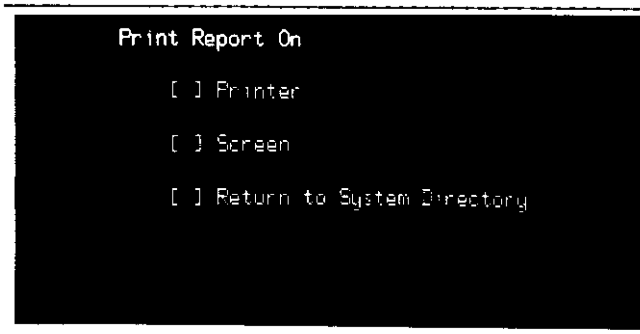


Figure 15:
Print Menu

A typical report may be to print out all of those instruments calibrated by an individual during a certain month. Figure 16, attached, is the first page of such a report.

Summary

Three types of traditional data bases were presented; linear, hierarchical, and network. The characteristics of these data bases were compared. A practical Calibration History Management System implemented on a microcomputer was described. This management system took advantage of the best attributes of the various standard forms of data base to optimize speed and storage capacity. The easy ability to reconfigure the data base for varying user requirements was emphasized.

Conclusion

The ability to store and manipulate a large data base on a microcomputer makes it possible for budget restricted facilities to maintain their own information system. BY building in easy reconfigurability, the user no longer has to rely on expensive programming time to customize the system for his own particular requirements.

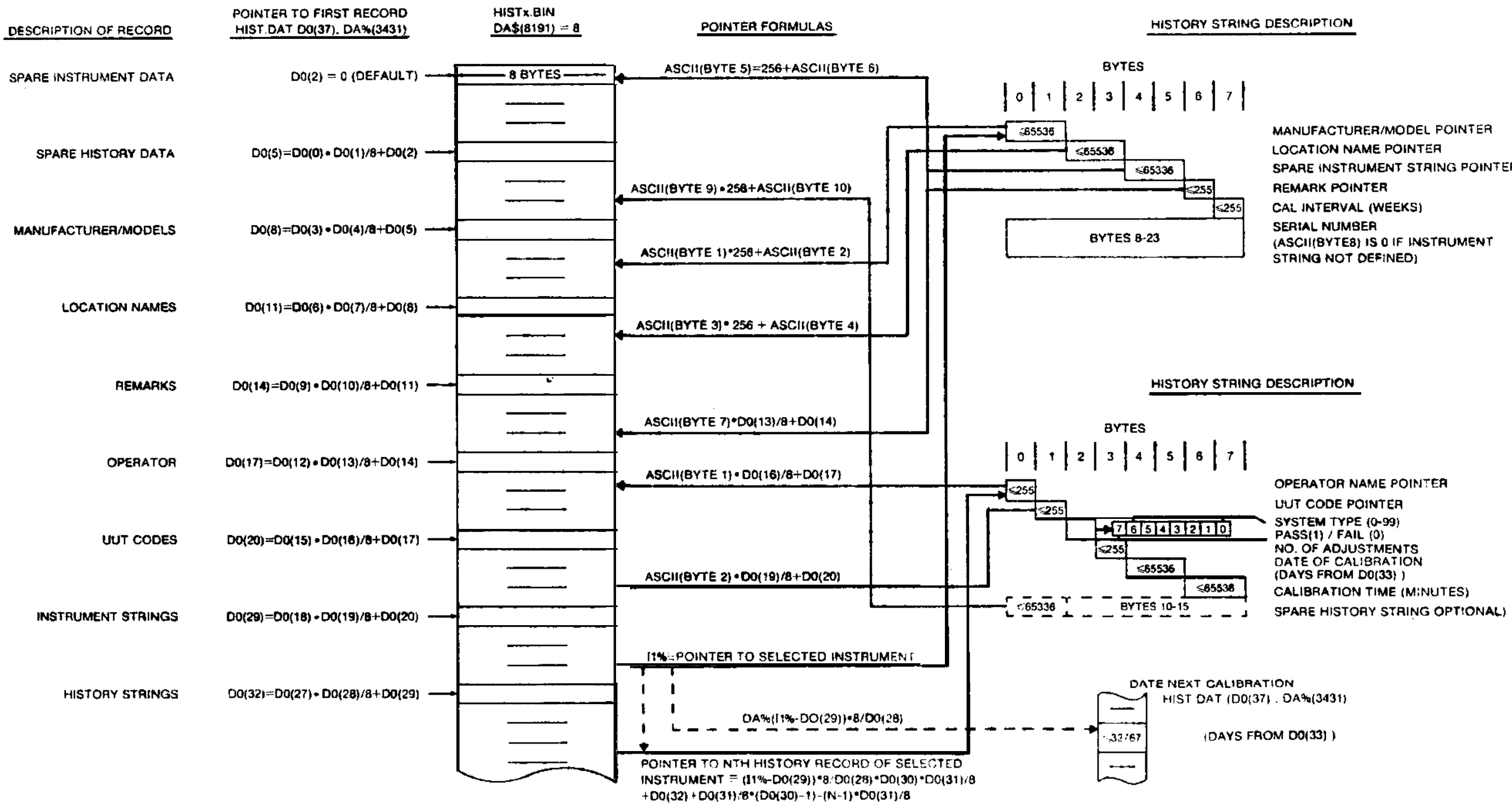


FIGURE 5: Calibration History Management System File Structure

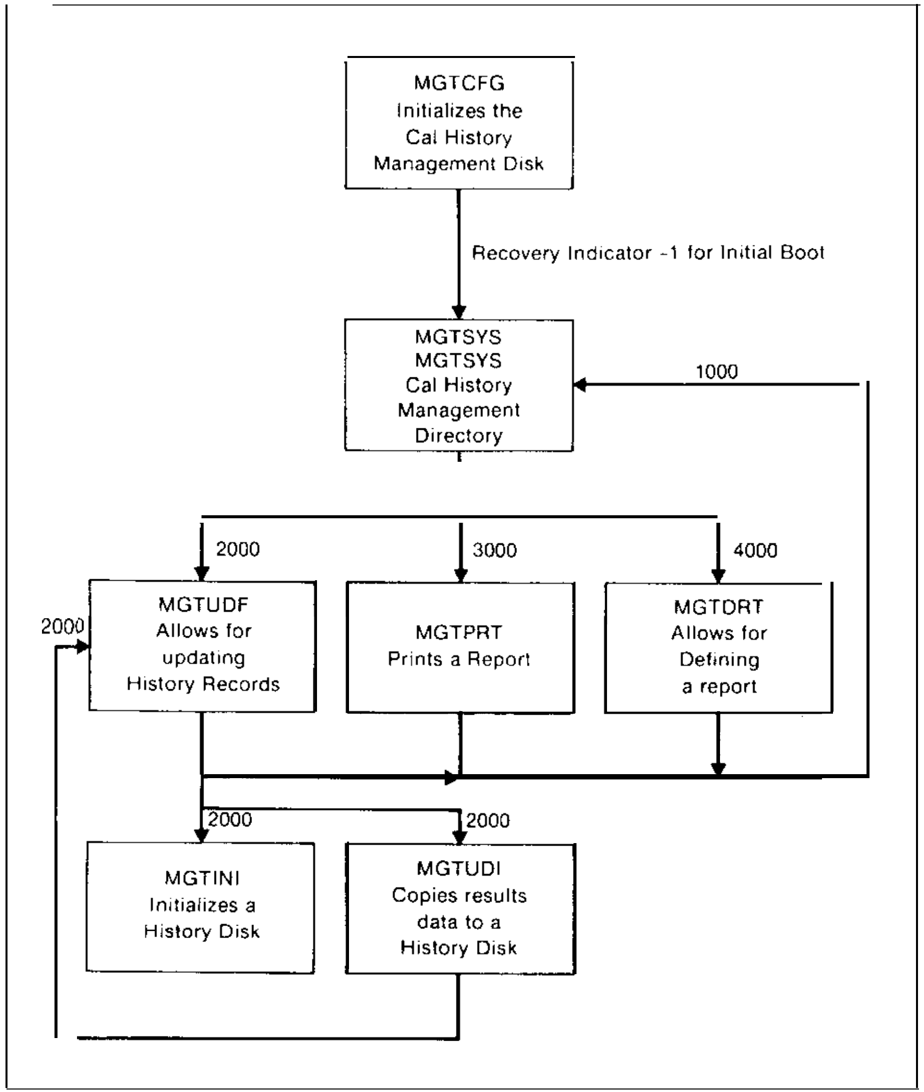


FIGURE 6: Calibration History Management System Software Hierarchy

CO(0) Total number of spare instrument strings allowed.

CO(1) Length of each spare instrument string.

CO(2) Pointer to first spare instrument string.

CO(3) Tot31 number of spare history strings allowed.

CO(4) Length of each spare history string.

CO(5) Pointer to first spare history string.

CO(6) Number of manufacturer/model numbers.

CO(7) Length of each manufacturer/model number string.

CO(8) Pointer to first manufacturer/model number.

CO(9) Number of location strings.

CO(10) Length of each location string.

CO(11) pointer to first location string.

CO(12) Number of remark strings.

CO(13) Length of each remark string.

CO(14) Pointer to first remark string.

CO(15) Number of operator name strings.

CO(16) Length of each operator name string.

CO(17) Pointer to first operator name string.

CO(18) Number of UUT code strings.

CO(19) Length of each UUT code string.

CO(20) Pointer to first UUT Code string.

CO(21) Tot31 number of blocks on MFO:.

CO(27) Number of instrument strings.

CO(28) Length of each instrument string.

CO(29) Pointer to first instrument string.

CO(30) Number of history strings per instrument string.

CO(31) Length of each history string.

CO(32) Pointer to first history string.

CO(33) Base year for date calculations.

CO(34) Revision number of software under which the Cal History Date Disk was generated

CO(35) Pointer to last dimensioned array on a Cal History Data Disk

FIGURE 7: Configurator Variable3 Definition

```
1020!-SPARE INSTRUMENT STRING-
1022CO(0%)=0%        ! NUMSER
1024CO(1%)=0%        ! LENGTH
1026CO(2%)=0%        !POINTER OF BEGINNING
1028!-SPARE HISTDRY STRING-
1030CO(3%)=0%        !NUMBER
1032CO(4%)=0%        ! LENGTH
1034 !                POINTER OF BEGINNING
1036CO(5%)=INT(CO(0%)*CO(1%)/8%+CO(2%))
1038!-MANUFACTURER/MODEL NUMBER STRING-
1040CO(6%)=300%      !NUMBER
1042CO(7%)=56%       ! LENGTH
1044!                 POINTER OF BEGINNING
1046CO(8%)=INT(CO(3%)*CO(4%)/8%+CO(5%))
1048!-LOCATION NAME STRING-
1050CO(9%)=50%       ! NUMBER
1052CO(10%)=56%      ! LENGTH
1054 !                POINTER OF BEGINNING
1056CO(11%)=INT(CO(6%)*CO(7%)/8%+CO(8%))
1058!-REMARK STRING-
1060CO(12%)=25%      ! NUMSER 1255
1062CO(13%)=56%      ! LENGTH
1064 !                POINTER OF BEGINNING
1066CO(14%)=INT(CO(9%)*CO(10%)/8%+CO(11%))
1068 !-OPERATOR NAME-
1070CO(15%)=20%      ! NUMSER <255
1072CO(16%)=16%      ! LENGTH
1074 !                POINTER OF BEGINNING
1076CO(17%)=INT(CO(12%)*CO(13%)/8%+CO(14%))
1078!-UUT CODE-
1080CO(18%)=50%      'NUMBER, <255
1082CO(19%)=16%      ! LENGTH
1084!                 POINTER OF BEGINNING
1086CO(20%)=INT(CO(15%)*CO(16%)/8%+CO(17%))
1088 !-TOTAL NUMBER OF BLOCKS IN MFD: IN MULTS OF 128 +14
1090CO(21%)=398%
1104!-HISTORY POINTER DATA-
1106CO(30%)=10%      !NUMBER PER INSTRUMENT
1108CO(31%)=8%       !LENGTH <=64
1110!-INSTRUMENT POINTER DATA AND SERIAL NUMSER-
1112!                 POINTER OF BEGINNING
1114CO(29%)=INT(CO(18%)*CO(19%)/8%+CO(20%))
1116CO(28%)=24%      !LENGTH <=64
1118!                 NUMBER (NOT > 3431)
1120CO(27%)=INT(((CO(21%)-14)*512-CO(29%)*8)/(CO(30%)*CO(31%)+CO(28%)))
1122IFCO(27%)>3431THENCO(27%)=3431
1124!POINTER OF BEGINNING OF HISTORY DATA
1126CO(32%)=INT(1*CO(27%)*CO(28%)/8%+CO(29%))
1128!PRINT OUT NUMRER OF INSTRUMENTS
1130PRINT'    History Disk wilt ho(d';CO(27%);'instruments'
1132!-BASE YEAR FOR @ATE CALCULATIONS
1134CO(33%)=1975%
1136!-REV OF SOFTWARE THIS HISTORY DISK WAS GENERATED UNDER-
1138CO(34%)=-9%
1140!-POINTER TO LAST STRING ON HISTDRY DISK-
1142CO(35%)=INT(CO(32%)-1%+1*CO(27%)*CO(30%)*CO(31%)/8%)
```

FIGURE 8: **Configurator Program Listing**

==

REPORT NAME: P.J. PLITT IN APRIL 1982

DATE: 12-Nov-82
TIME: 10:11

==

Manufacturer/Model	FLUKE 8000A
Serial Number	0000906
Location Name	PLANT 1
Date Next Calibration	27 Apr 1983
Calibration Interval	52 weeks
Remark	

Operator Name	P.J. PLITT
UUT Code	
System Type	7405
Pass/Fail	Pass
Number of Adjustments	0
Date of Calibration	27 Apr 1982
Calibration Time	12 minutes

Manufacturer/Model	FLUKE 8920A
Serial Number	2285023
Location Name	PLANT 2
Date Next Calibration	29 Apr 1983
Calibration Interval	52 weeks
Remark	

Operator Name	P.J. PLITT
UUT Code	
System Type	7405
Pass/Fail	Pass
Number of Adjustments	1
Date of Calibration	29 Apr 1982
Calibration Time	17 minutes

Manufacturer/Model	FLUKE 9318
Serial Number	70932
Location Name	PLANT 1
Date Next Calibration	27 Apr 1983
Calibration Interval	52 weeks
Remark	

Operator Name	P.J. PLITT
UUT Code	
System Type	7405
Pass/Fail	Pass
Number of Adjustments	0
Date of Calibration	27 Apr 1982
Calibration Time	13 minutes

Manufacturer/Model	FLUKE 6011A

FIGURE 16: Calibration History Management System Example Report

An Automated Vibration Calibration System

Philip Benoit
Naval Weapons Station Seal Beach
Metrology Engineering Center
Pomona, California

Mark Kaufman
Ford Aerospace and Communications Corp.
Newport Beach, California

Abstract

The calibration of accelerometers and velocity transducers is a growing problem for the Navy. As more of these sensors are incorporated into systems the demands on the limited calibration resources have increased sharply. The Navy chose to automate the vibration systems to solve this problem. The system design criteria and the approaches used are described. The automated vibration calibration system used both software and hardware techniques to overcome the problems of increasing workload and decreasing resources.

Introduction

In the Navy vibration calibretion program, there are two types of sensors requiring support: accelerometers and velocity transducers. Accelerometers are calibrated over a frequency range of 5Hz to 10,000Hz, with an amplitude range of lg to 50g's. Velocity transducers are calibrated over a frequency range of 10Hz to 2000Hz, with an amplitude range of 0.5in/sec to 10in/sec. Velocity transducers pose an additional problem because some types can weigh up to 5 pounds and therefore require a large shaker and drive amplifier. The vibration systems used by the Navy in the late 1970's were between 10 and fifteen years old. The old tube amplifiers and the shakers were nearing the end of their useful life.

The Navy's Metrology Engineering Center at Pomona was tasked to develop solutions to these problems. The basic requirements for the system were to cover the required frequency and amplitude ranges with 3% accuracy. The operation of the system also had to meet human interface requirements . The system had to be easy to use, understandable, operate in a manner the technicians were used to, and be configured in a manner that would assure proper calibration of the units under test, UUT'S. The approach chosen was to use off-the-shelf equipment with an updated shaker and amplifier. Two versions of the vibration calibration system were designed, an automated and a manual system. The automated systems were to go to the four labs with the highest workloads. The remaining ten facilities were to receive the manual system. The manual and the automated systems are the same except for an instrument controller and a printer. The basic calibration method is to compare the standard accelerometer's output voltage at a known g level and frequency to the accelerometer or velocity transducer under test. Using the known characteristics of the standard the sensitivity of the unit under test is calculated.

System Description

Figure 1 is a block diagram of the automated system. The shaker and amplifier provide the stimulus. The drive signal for the amplifier is produced by a signal generator. The measurement system consisted of a digital RMS voltmeter. A signal selector and a display module were the only two "special" units in the system. The display module generates horizontal sweep Signals for an oscilloscope to display a fixed number of cycles, independent of frequency.

The automated part of the system consisted of a desktop computer used as an instrument controller and a printer. The instrument controller was equipped with an IEEE-488 bus and a 16 bit input/output interface. The controller gets a list of the test to be performed from a tape. The controller then sets output of the signal generator and reads the measurements taken by the voltmeter. Then the results are computed and formatted for the printer.

Hardware Details

The shaker, an Unholtz-Dickic 1068, is capable of sinusoidal motion of up to 50 g's over the frequency range of 5Hz to 10kHz. The standard accelerometer and the uur are mounted on the shaker table. Special attention was paid to the design of the mounting hardware to avoid introducing distortion. The alternating current driving the shaker is pro" i ded by the power amplifier, an Unholtr-Dickie A100-6. The signal generator is the source of the sinusoidal vol tage. A Fluke 6011/AA synthesized signal generator was used in this system. This is a programmable instrument and is the means of controlling the g level and frequency of the shaker. The output of the 6011/AA is stable enough to avoid using a separate frequency counter for monitoring. The standard accelerometer used in this system is a piezoelectric accelerometer and amplifier. The units are cal i brated at a Navy primary lab. The tolerance of the standard accelerometer is 3% from 10Hz to 50Hz, 2% from 50Hz to 2000Hz, and 4% above 2000Hz. The heart of the measurement system is the digital voltmeter. The one selected for this system is the Fluke 8502A-09A/AA. The first systems were built using the 8500 until the 8502 became a standard within the Navy. The 09A/AA option is a modified RMS module allowing lower frequency measurements. The accuracy of the "01 tmeter and RMS converter is +/- 0.5% over the 5Hz to 10kHz frequency range. Since sampling rates and filter constants are programmable, the voltmeter is 'tailored' to the frequency and ampl i tude to be measured. One minor peculiarity of the 09A/AA option is all readings are multiplied by i factor of ten. This is because of the modification to the input circuits to a1low the 5Hz measurements. The signal selector in the system is programmable over the controller's 16 bit input/output bus. The signal selector consists of a relay, some indicators and a function/manual override switch. The 16 bit interface controls and monitors the position of the relay. This was done to test for either a relay failure or the function switch being in 'manual ." The system also included an oscilloscope control led by a sweep synchronizer. The sweep synchronizer controls the horizontal drive of the oscilloscope to show only three or four complete cycles at a time. The use of this device was mandated by the speed of the system. Manual control of the oscilloscope would not have kept up with the rapid frequency changes. The osci11oscope itself is a Tektronix 5011. The sweep synchronizer and the signal selector are in Tektronix TM 500 modules and are mounted in a TM 503 mainframe.

Software Details

Software is important in an autanated system, however being important does not mean software is magic. The process of calibrating accelerometers or veloci ty transducers is the same for a manual or an automated system. The first item required is a list of the test points. Each frequency and amplitude at which the UUT wi 11 be cal ibrated must be known. During the calibration, the frequency is set and the shaker drive adjusted until the correct level is obtained. The outputs from the UUT and the standard are then measured and compared. Finally, a report of the results is generated. The software of this system performs the same process. The list of the test points is obtained from a test matrix stored on tape. For each test point the g level or velocity is set to the correct level and the outputs measured and compared. A report showing the test points used, the standard used and the results obtained is generated at the end of the test. Each part of the process is performed near1 Y the same way a human operator would. The difference being the machine is not as smart, but is faster.

A calibration of either an accelerometer or a velocity transducer follows the flow chart of figure 2. After getting the correct test matrix and initializing the system the controller begins a loop. Each complete loop executes the level set routine and the measure routine. After all the test points have been run, the controller begins the printout of the report. There are some slight differences in settling time constants between the velocity and accelerometer programs, and, of course, the printouts and test points are different. The process is the same. The test matrix can be changed, but the printout of the calibration data will show what points were used. This allows the freedom to adapt to new UUT's, but still controls the process. A test matrix for an accelerometer is illustrated in figure 3. The first column is the g level, the second, the frequency of the test points. The third is the signal level needed from the signal generator to produce the desired g level at the frequency of test. The fourth column is the sensitivity of the standard accelerometer at the frequency and g level of the test point. The fifth column is the expected output of the standard at the correct frequency and amplitude in mV RMS. Included as part of this test matrix is the manufacturer, model and serial numbers of the standard. This data is printed out in each report.

The level set routine is illustrated by figure 4. The process of setting the correct amplitude level closely parallels the way it would be done manually. one of the columns of the test matrix is the expected level of the signal generator to produce the desired voltage reading from the standard. There is a housekeeping program that determines this experimentally. The Easyoff subroutine makes the transition from one frequency or level to another easier on the system by slowly incrementing the current level to the expected one. The actual process of setting a level involves a number of tries. If the voltage from the standard accelerometer is within 0.08% of the required level, then the subroutine returns to the main program and starts the measure routine. If the measured level is not close enough, a correction is calculated. The proposed level is checked against the expected signal generator level. If the difference between the two amounts to more than 25% of the expected level, a fault is assumed and the system shutdown. This is one of the precautions taken to protect the system and the UUT. A count of the number of tries taken is kept. If the measurements are unstable for sane reason, or the shaker's output is changing, this routine will shutdown the system. The loop continues until the g level is at the expected value or a shutdown occurs. When the g level is correct, then the measure routine begins. At the conclusion of a calibration the new levels are recorded. This way the system 1earns the new drive levels for each test point. By updating the levels the operation of the system is speeded up because the difference between the expected value and the value needed will only be the degree of drift in the amplifier and the shaker.

The measure routine is actually very simple. The vol tmeter has been programmed for the correct frequency in the level set routine. The voltmeter is programmed for a frequency by setting the filter time constants and the sample rates. The measure routine takes ten readings and looks at the maximum difference between the readings. In the case of the standard and test accelerometers this difference must be less than 0.1%. The maximum difference al lowed for the ueloci ty transducers varies with the accuracy of the transducer. This test was included to insure the readings were not changing over the measurement period. The ten readings are then averaged to provide the measurement. To minimize any changes during the measurement cycle, the UUT and then the standard are measured. The actual value of the standard is used to calculated the amplitude. For example, values of 4.99 instead of 5.00 g's are calculated. However, the 4.99 value is a real measurement, not an assumed value.

A sample printout is shown in figure 5. Each test point and the UUT's sensitiuity at that point are shown. The g levels are not ● "e", because the actual ual ues were measured and recorded, not assumed. The model number and manufacturer information about the standard and the UUT are included in the report.

There are a number of housekeeping programs. There is one to edit the master test matrix. Every test must be in the master matrix to be used. The master matrix is used in another program to experimentally determine the drive levels needed for each test point. There is another program to select which tests will be used for a particular UUT.

Results

The integration of the hardware and software produced a system meeting the requirements. one Of the most obvious benefits of the system was the decrease in test time. A cal ibrat ion of an accelerometer using the automated system will last about six to twelve minutes. The ueloci ty transducer calibrations last eight to twelve minutes. The manual test time for a velocity transducer is nearly an hour. A direct comparison between the manual and automatic accelerometer cal i brat ions shows a similar improvement. The range in times is due to variations in the number of test points and the length of time required to reach a level. Consistency is another benefit of the automated system. Since the automated system generates a printout for each calibration, there is no doubt or confusion about what was done.

One side effect Of the automated system was to force a close look at the vibration measurements. The automated system will not work correctly if there are ground loops, or problems with the shaker or amplifier. The unforeseen pr i cc of precision and speed is everything must work precisely. Technicians can compensate for many problems, the automated system can only compensate for a few. Everything from UUT mounting to cable routing caused problems for the automated system. Improper UUT mounting can cause distortion or decreased high frequency response. Accelerometer can have to be isolated from the shaker body or noise is introduced. Power system grounds also introduced noise. During the early stages of development a very old and tired shaker and amplifier were used. Much of the software was written to avoid the affects of the shaker's deteriorating condition and to avoid increasing the rate of deterioration. Solving these problems also made the manual version of the system work better.

Conclusions

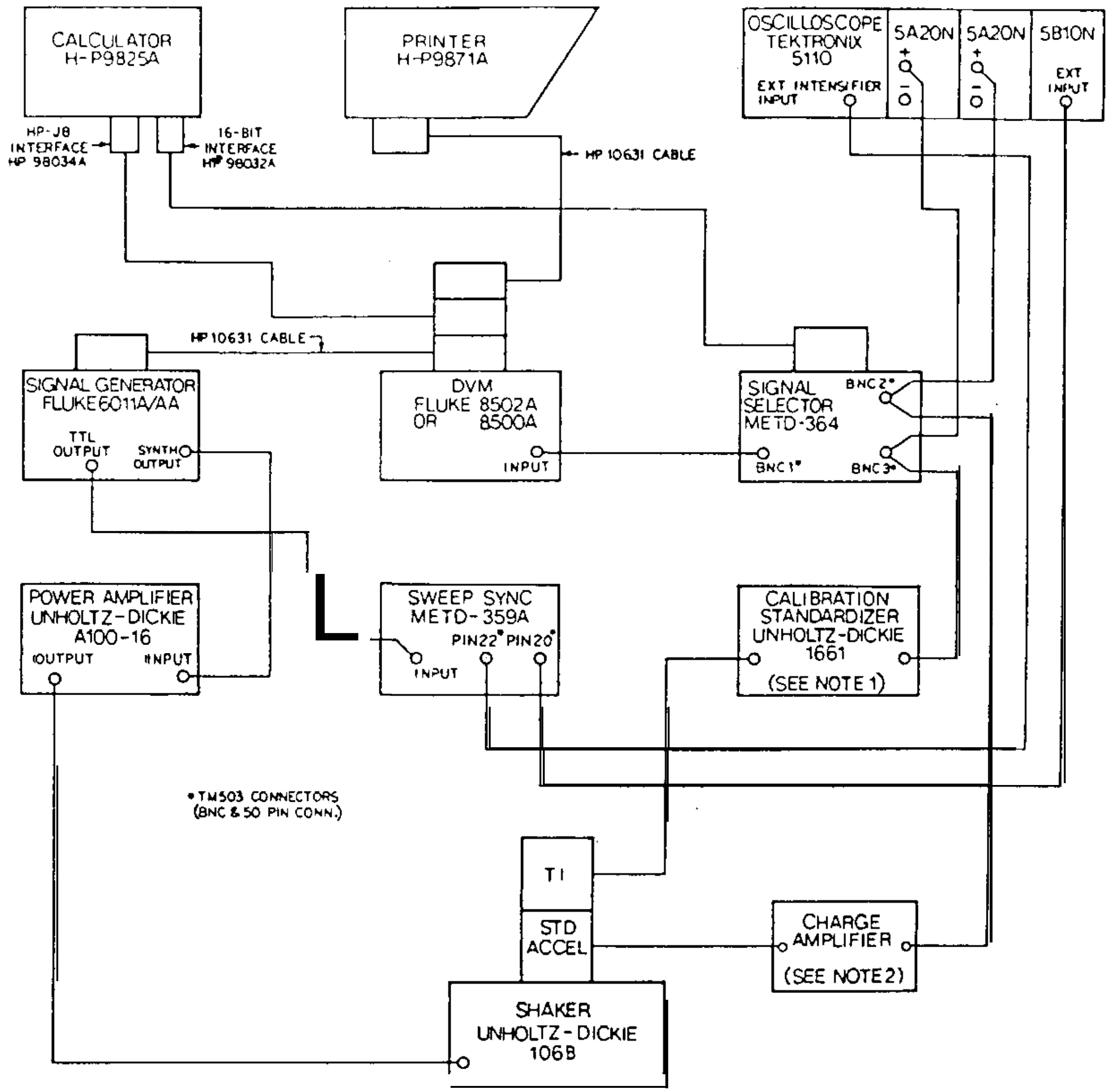
The lessons learned during the development of this system can be applied to other systems as well. Nearly all manual test systems can be automated. The most direct way of translating manual steps into software is to observe the process in detai 1 and duplicate it using software. Some portions of the process cannot be done exactly the same, and this is where many unforeseen problems will occur. By closely parallel ing the manual process, the automated process is kept understandable. The human interface is very important. Remember the operator is there, even if he is not interacting with the system. The system display should tell the operator what is happening, what frequency, which g level, etc. should be displayed to give the operator some feel of what is going on. If the same operators are going to use the system after automation, then their interaction should be kept nearly the same as before. This eases the transition from manual to automatic.

The accuracy of the system is limited by the accuracy of the standard accelerometer. Further increases in accuracy will follow improvements in the standard. Another possibility is to use a different technology for a standard. G level is determined by motion, and motion is determined by position and time. A laser "rangefinder" could be used to determine the instantaneous position. From this position information, motion and acceleration could be calculated.

The outstanding lesson of this project is there will be problems that have nothing to do with automation. The shift to automation revealed problems caused by increasing workload and more stringent requirements. Any real improvement in the vibration measurements would have discovered these problems. However these problems did have to be solved while automating. If there were problems before automation, there certainly will be after.

Ref • r*nc*

Technical and Fabrication Manual, MET-D-422 Automated Vibration System, Navy Metrology Engineering center, Naval Weapons Station Seal Beach, Pomona Annex, Pomona California 91769, 1 July 1982.



NOTE 1: CALIBRATION STANDARDIZER IS NOT USED WHEN CALIBRATING VELOCITY TRANSDUCERS.

NOTE 2: USE THIS CHARGE AMPLIFIER THAT WAS CALIBRATED WITH THE STD ACCELEROMETER BEING USED -YE REPORT OF CALIBRATION.

Figure 1 System Block Diagram

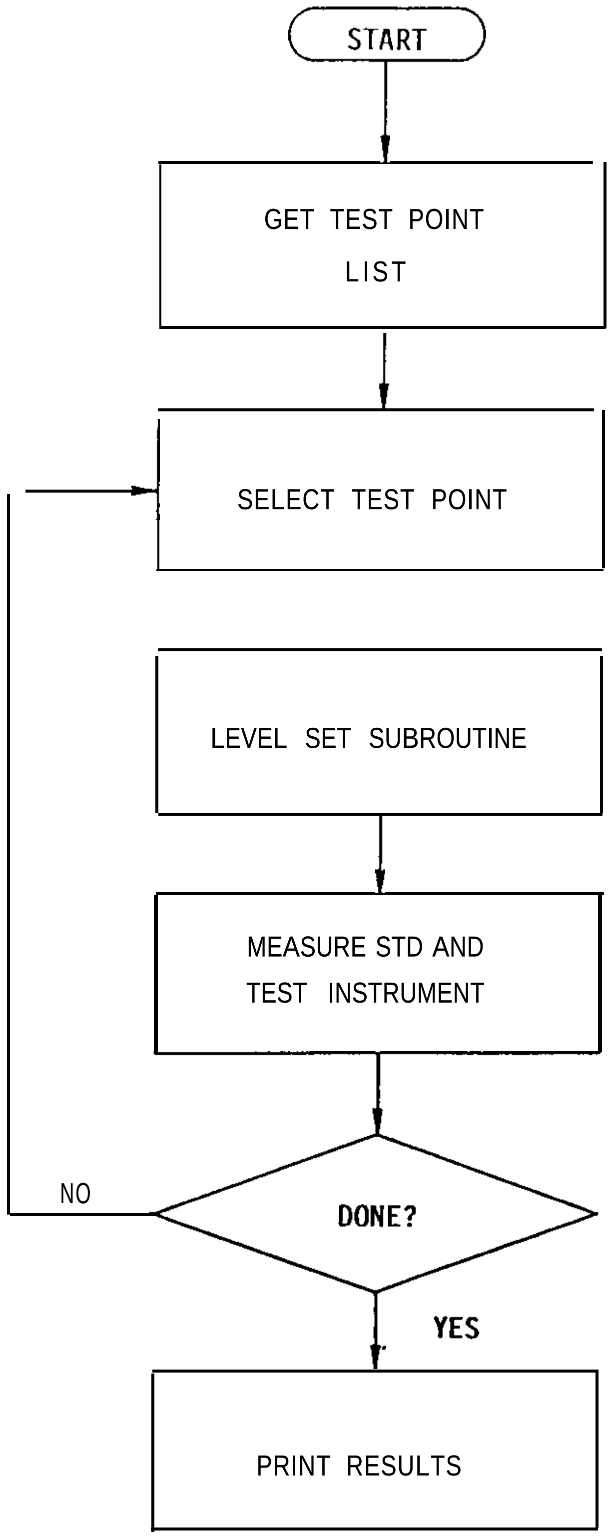


Figure Calibration Process

ACCELEROMETER TABLE

G Level G's	Frequency Hertz	Drive Volts	STD Sensitivity mV/G	STD output mV
1.5	10	2.168	10.13	10.74
5.0	30	2.249	10.04	35.49
10.0	100	1.560	10.00	70.70
10.0	400	0.578	10.00	70.70
10.0	1000	0.578	9.98	70.56
10.0	1500	0.695	10.06	71.12
10.0	2000	0.695	10.08	71.27
10.0	2500	0.866	10.01	70.77
10.0	3000	0.866	10.10	71.41
10.0	3500	0.866	10.07	71.19
10.0	4000	0.655	10.08	71.27
10.0	4500	0.655	10.06	71.12
10.0	5000	0.545	10.07	71.19
10.0	5500	0.453	10.07	71.19
10.0	6000	0.259	10.05	71.05
10.0	6500	0.151	10.09	71.34
10.0	7000	0.054	10.13	71.62
10.0	7500	0.177	10.08	71.27
10.0	8000	0.312	10.17	71.90
10.0	8500	0.388	10.12	71.55
10.0	9000	0.457	10.11	71.48
10.0	9500	0.545	10.07	71.19
10.0	10000	0.453	9.99	70.63
2.0	1000	0.120	9.98	14.11
5.0	1000	0.265	9.98	35.28
10.0	1000	0.579	9.98	70.57
20.0	1000	1.257	9.98	141.14
50.0	1000	0.000	9.98	352.85

For Standard: Manufacturer: KISTLER
Model Number: 808K/561T
Serial Number: 877/558

The column headings are explained as follows:

Column 1 – Shaker output in g's

Column 2 – Shaker frequency

Column 3 – voltage required to drive power amplifier

Column 4 – Sensitivity of standard accelerometer

Column 5 – Standard accelerometer output in mV

Figure 3 Test Matrix

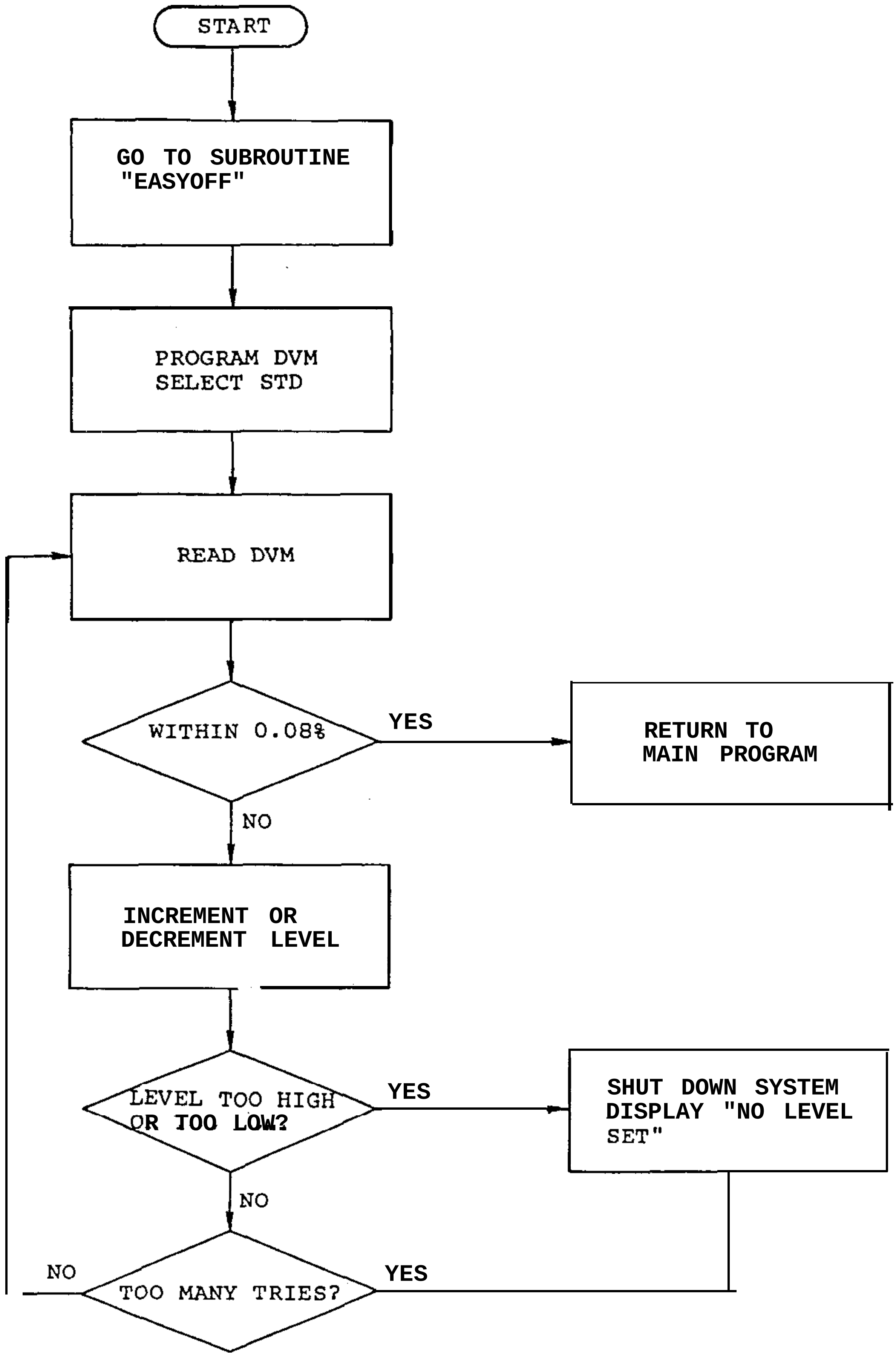


Figure 4 Level Set

REPORT OF CALIBRATION

FOR

Accelerometer
Model 2217C
S/N HA59

Using the Automated Vibration System
Standard Used:KISTLER 808K1/561T SN 5032/2008

G Level G'S	Freq Hz	Sensitivity pC/G
4.99	30	27.64
9.97	100	27.66
10.02	400	27.64
10.01	1000	27.63
10.01	1500	27.60
10.01	2000	27.71
10.01	2500	27.60
10.01	3000	27.28
10.01	3500	27.39
10.01	4000	27.20
10.01	4500	26.97
10.01	5000	26.79
2.00	1000	27.66
5.00	1000	27.65
10.01	1000	27.63
15.01	1000	27.64
20.00	1000	27.65

DATE: 12/4/81

SUBMITTING ACTIVITY: MEC

Figure 5

CONTEMPORARY APPLICATIONS ROBOTS

Leonard B. Gardner
ScD, LLB, P.E., CMfgE
AUTOMATED INTEGRATED MANUFACTURING'

INTRODUCTION

This paper is intended to illustrate, to a group of engineers primarily engaged in measurement sciences, the major contemporary applications of industrial robotics. It assumes that this group has heard and read much genera1 information about robots. This has arroused their curosity for a concise in-depth authoritive summary of this fast growing branch of science and technology. The science o f robots involves the complex interactions of coordinate transformations (in six degrees of-freedom), optimal and adaptive control systems, neurological modeling, artificial intelligence and the common thread of computer programming that "puts this all together for use by the technologist." These subjects are mentioned only to give the reader a" idea of the sophistication and complexities of industrial robots. They are far too vast to treat in this paper and So their details have bee" properly excluded from further discussion. The technology of robots considers the science to be mainly transparent to the user. It is concerned with applications "here industrial robots can be used primarily to increase productivity. Here, productivity equates to the cost of manufacturing a finished product. Certainly there are other benefits from robots such as the ability to remove workers from a hostile environment and the reduction in material Spoilage and accidents. However, the main concern is with increasing productivity.

So, the implication is that industrial robots can help you make a better product for less cost while improving worker safety -- at least in certain instances. But exactly "hat is this robot? Apparently, the word was first used in 1923 by a Czechoslovakian playwrite, Karel Capek in "R.U.R. - Rossum's Universal Robots." A few years later, Charlie Chaplin in "Modern Times" mimicked the American worker on the automated production line, perhaps inspired by R.U.R. I" 1942 Isaac Asimov crystallized the "Three Laws of Robotics" and in 1950 his book, "I Robot" which was a collection of nine previously published stories came out. In the mea" time (late 40's) George Devol began his experiments with the transfer mechanisms that was later called a Programmed Article Transfer and was awarded US Patent No 2,988,237 in 1961. Still later, in the mid 60's, Joseph Engelberger realized the potential of this invention and bought out George. Several more years were required before the first industrial robot was sold in 1961, for die casting. Even the", growthwas slow (Unimatio" did not show a profit until 1975) and manufacturers of robots did not polificate until the late 70's "he" there were about 200 early developers, many of whom abandoned their effort. In the Orient, almost anything that replaces a human in performing even the simplist of tasks is called a robot. Thus they consider as robots both a hoist to move Steel bars and an assembler that puts together the insides of the modern VLSI chip. Closer to home, the Robot Institute of America has defined a robot as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks." By the first definition, in 1980 Japan had 47,000 robots installed and working, however, by the second definition (generally acceptable in America) the number shrinks to 3,000. Today's industrial robots have three major components: manipulator, controller and power supply. The manipulator consists of mechanical links and joints, capable of moving in various directions; actuators, that drive the mechanisms either directly or indirectly through gears, chains,, or ball screws; control valves that adjust the flow of fluid to the actuators; and feedback devices that sense positions of the links and joints and feeds these data to the controller. The controller directs the movements of the manipulator, stores position and sequence data, and interfaces the robot with the real outside world. The power supply may be electric, hydraulic, or pneumatic and provides regulated energy for the manipulator's actuators. Scientists add to this list a few capabilities not generally available off-the-shelf

*Automated Integrated Manufacturing
2406 Buttetop Place
Bprlng Valley, CA 92076
619.464-2446

today. These capabilities are locomotion in a specified environment, perception and interpretation of its environment in terms of a task and heuristic problem solving or the ability to plan and direct its own actions in order to achieve higher order goals.

A few years ago, when one thought of industrial robots, they thought of spot and arc welding, spray painting and assembly. Many such applications still use the most robots in terms of the value of equipment installed. But mining, equipment repair and farming (just to mention a few) are comming up close behind. Domestic robot manufacturers appear to fall into four groups: traditional manufacturers of machine tools, established speciality manufacturers, large general purpose manufacturers, and small entrepreneurial and innovative firms. The relative importance in the market place of these different types of firms will depend on, and in turn influence, the evolution of robotics technology.

COMMERCIALLY AVAILABLE ROBOTS

It is convenient to introduce commercially available robots by their machanical configuration and their classification. Mechanical configurations are characterized by coordinate systems and degrees-of-freedom. The classification of robots made by the Japanese Industrial Robotic Association (JIRA) consists of the following six types:

1. Manual manipulators that are worked by a" operator.
2. Fixed sequence robots that perform successive steps of a given operation in a predetermined sequence.
3. Variable sequence robots where the sequence of steps may be easily changed.
4. Teaching mode playback robots that repeat instructions after being taught a work procedure.
5. Numerical-controlled robots that execute operations on the basis of numerically coded information.
6. Intelligent robots that perform various functions through its sensing and recognizing capabilities.

Robots are available in four coordinate systens: rectangular (Cartesian), cylindrical, spherical (polar), and jointed-spherical (revlolute). The work envelop in rectangular coordinates is the x,y,z axes. Typical robots of this configuration are:

Advanced Robotics Cyro 750
General Electric AW7. Al2 Allegro
IBM RS-1
Mobot (most models)
Westinghouse 5000, 7000

The work envelope in cylindrical coordinates is the r,θ,z axes forming a portion of a cylinder. Typical robots of this configuration are:

ASEA MHU
Cybotech H80 H8
IBM 7535
Prab Servo E., FA. FB and FC
Seiko

The work envelope for spherical coordinates is the r,θ,Ø axes forming a portion of a sphere. Typical robots of this configuration are:

Bendix AA160
General Electric GP66
Prab, Non-servo 4200
Unimation 1000 ect

The work envelope for revolute coordinr1, θ1, 0, r2, θ2, 02, axes forming a" approximation of a porition of a sphere. Typical robots of this configuration are:

Advanced Robots Cyro 820
ASEA IRb-6, IRb-60
Bendix ML 360
Cincinnati Milacro" T3
DeVilbiss Trallfa
Unimation Puma
United States Robot, Maker

The major axes of motion relate to the robotic arm moving in and out, up and down, and rotating about the base. I" addition a minor axes of motion is related to the effector placed at the end of the robotic arm and sometimes referred to as the wrist. The motion of the joint between the effector and arm are:

pitch, a" angular motion in a vertical plane through the last major axis.
yaw, an angular motion in a horizontal plane through the last major axis.
roll, an angular motion in a plane perpendicular to the last major axis.

Additional one and two axis motions of the entire robot may be provided by mounting it on a traverse mechanism attached to the floor or to the ceiling.

The characteristics of robots follow from their classification. Manual manipulators are like those of a hot cell or hoist. Fixed or variable sequence robots may be controlled by a sequencer or by a servo motor. Non-servo sequencers have a controller that initiates and sequences all operations. Limit switches signal when the proper position is reached and stop the motion. I" general, there are only two static positions for each axis. This mode of operation is commonly used on smaller robots; but, it may also be applicable to larger robots. Relatively high speeds are possible and repeatability is usually to within 0.01 inch. On the other hand, the servo controller addresses the memory location of the first command position and also reads the actual position of the various axes. These two sets of data are compared and their differences used to adjust the position of the robot. This process continues until the differences are effectively reduced to zero. With this system, the robot can move and stop anywhere within its limits of travel. Programming is accomplished by manually initiating signals to servo valves to move the robot to a desired position and then recording the differences in a computer memory. Smooth motions may be executed while controlling acceleration and velocity. Subroutining and branching capabilities permit this robot to take alternative actions. Accuracy of positioning the end of the arm usually varies between 0.125 and 0.001 inch.

Teaching playback robots employ point-to-point servo-control sequencer and potentiometric controls. They are tedius to program. However, unlike a simple servo-control, the programming positions can be easily modified during program execution. The actual path followed by the robot between points is not controlled and may be different from the path followed during the teaching process. That is, the coordinate data are sampled on a time base rather than discretely determined points in space. Usually more than one program may be stored in memory and randomly accessed. Generally, these robots are smaller in size and lighter in weight than the point-to-point Servo robots.

Numerical-controlled robots are programmed off-line from their operation typically by means of a special purpose high level language. Some more common languages and also some special purpose languages have bee" used. The time location of the robotic joints are referenced by coordinate transformations to some fixed point. These become input data to a control system that follows a motion axiom to constrain velocity and acceleration of the joints. A great amount of flexibility is permitted with program selection, modular modification and operation.

Intelligent robots are the highest class. They are still in development. With this robot an objective of the movement and any constraints are given in English like instructions. The robot is then otherwise free to achieve the objective.

JUSTIFICATION FOR ROBOTS

Robots aid in achieving increased productivity more as the result of the consistancy of the robot's pace rather than the rate of the pace which may not be much different than for ma". Thus, the robot's higher productivity is measured in terms of increased parts per day. This consistency of operation also results in improved quality and rejection of scrap. For example, in die casting and plastic molding, consistant cycle time of the robot loading and unloading allows die temperatures to stabolize and operation without shutdown for breaks and shift changes avoids the production of scrap cold-shots. In another example where a robot applies a spray coating, greater consistancy in thickness of layer is achieved and overspray is reduced. The application of robots can allow people to be removed from noisy, dirty, dusty, hot (and noxious fumes) working conditions and monotonous, fatiguing jobs. Why change the conditions or the work when it is cost effective to use a robot instead of a human? Certainly in the long run, the robot is the least costly of several alternatives. Robots reduce the cost of direct labor, spoiled work, indirect supplies, supervisory labor, and training while increasing output, saving energy, and providing a" investment tax credit. In evaluating the cost of a" industrial robot for these comparisons, the cost of installation, rearrangement and modification of equipment; other required facilities; tooling; maintenance supplies, tools and labor; training; taxes and insurance; application engineering and the cost of capital.

APPLICATION DEVELOPMENT

The first thing to do in developing applications for robots is to become familiar with the basic capabilities and limitations of those that are available. Then make an initial survey of potential applications. Look for tasks that are within the robot's capabilities, that do not require judgement by the robot, and (most important) that justifies the use of a robot. IF this initial survey yields a list of potential applications, then make a more detailed study and pick the first application. I suggest the simplist job on the list be picked for the first application. Now, study the job and make certain you know everything a ma" has to do to perform the job. Try to anticipate all the things that could go wrong with anything associated with the job. NOW select a robot with sufficient reach, speed, memory, program and load capacity to do the job. Provide some extra capacity if possible. Consider if the robot should be protected From the environment. Make a layout of the installation locating interfaces to other equipment and identifying any facility changes required. Make provision for utilities, interlocks and guards. Provide the necessary effector and look at the alternative way by which a part could be picked up. Provide for backup equipment or plan to protect production when the robot is down.

IMPLEMENTATION OF ROBOTS

Do a much of the planning for the robotic installation as possible before the robot actually arrives for installation. Most important, prepare and train all levels of personnel at the site for the robot. Anticipate some Start up problems. Generally, programs may have to be refined, tooling adjusted, timing and interlocks tuned in. After installation, closely monitor the operation. Keep track of down time to identify recurring problems. Compare estimated and actual cost and performance. Develop a" in-house capability for programming and maintaining the robot. Lastly, give your own people total responsibility for the robot's performance.

TECHNOLOGY AND MARKET ISSUES

What types of manufacturers will play the most significant roll in the production of robots and their innovative use? Will robot use and production be concentrated in a few large companies? Will a variety of robots be available for many applications by diverse types and sizes of Users? What will be the effects of financial health of different types of potential producers and Users? Should R&D stress applications or should it focus on fundamental work aiming at a significant new breakthrough in the state-of-the-art? What roll should the Federal Government play in funding this research? What type of work should be pursued in Government research laboratories and at what level should it be funded? What additional policies, if any, would be required to stimulate R&D in the private sector? Are there particularly important apaplications of robots in the Federal Government that should be explored and developed? Should the Government encourage the establishment of technical standards for robotic devices and components? Should standards be set for interfacing robots with other automation and information technology? These, and other questions, are important questions that must be addressed at a" early date; now is the time for action and for direction! HO" technology is addressed will determine the market and influence the structure of the robotics industry.

SOCIAL ISSUES

Much of the literature on robotics contains references to the contribution toward improving industrial productivity that can be expected. It is important for US to examine this issue. No person or group are in agreement with others on this subject. But they do agree a simplistic solution that exaggerates the importance of robotics is not possible. There are two reasons. First, robotics is only one part of a wide array of technologies available to automate manufacturing and increase productivity. Second, productivity is a subtle and complex concept with several definitions and measurements. It depends on many factory that interact with one another. It is difficult! therefore, to attribute productivity improvements to any single technology. These warnings do not suggest robotics is unimportant for production, rather, they emphise the dangers inherant in taking a" overly "arrow definition of technology when assessing impacts on industrial productivity. Robotics can open up new business oppertunities for specialized equipment and application software. Robotics can lower the minimum scale for efficient production and create new manufacturing oppertunities for small business. However, the adoption of robotics by larger firms may foreclose some manufacturing oppertunities for small firms that cannot afford to invest in new equipment. To further the applications of robotics requires investment capital. There does not Seem to be a lack of such capital but a tax policy that encourages such investment is a" important stimulus to rapidly push this technology forward.

Unemployemnt is a" issue that is constantly raised when the social impact of robots is discussed. Productivity improvements, resulting from the use of robots, can affect labor in a number of ways Such as changing the relative proportion of machinery to workers, changing the demand for consumer products resulting from a change in pricing, and the supply of qualified workers with Specific skills. Employment in a particular industry may fall because fewer workers are need to automatically produce a particular product. But increses in production volume to meet a" increased demand could cancel or eve" turn around a decline in the work force. Most expert have argued more jobs are created by a new technology than there are eliminated, however, they are in different industries and require different skills. The effect on a" induvidual who has been replaced by automation can be traumatic. Without question, robotics will improve working conditions and job satisfaction. Robotics can also be a definite aid to the handicaped. Where the these benefits are realized depends, in part, on the particular ways in which industry uses the technology. Some feel the long-term effect of robots may be to "deskill" labor, requiring less ability on the part of humans. Some have expressed concern that robotic automation provides increased oppertunities for employer surveillance of employees. Unions feel employers having robots will "downgrade" jobs. However, all generally agree that workers with improved technological literacy Will be better able to oversee the operation of robots, would be less likely to resist introduction of robots, and would be easier to retrain.

MARKET VALUE OF ROBOTS

To study the market value of robots, we look toward Japan, who for many years has lead the world in the manufacture of robots. Their industry is growing faster than eve" they previously estimated. JIRA forcast in 1979 that Japan's shipment of robots would be ¥36B while actual shipments were ¥42B, an increase of about 17%. Early forcasts of shipments of robots for 1980 was ¥43B and later was revised ¥65B; actually, it was ¥78B, an increase of about 20%. This growth has continued. Forcast for 1985 in ¥500B and by 1990 this rises to ¥1T(500B$). It is also useful to note that the value for true robots shipped (playback, NC and intelligent systems) is increasing, while the value for fixed and variable sequence machines in decreasing. Another interesting statistic: between 1979 and 1980 the number of installed and operating Japanese robots of all types is increasing by 135% while the increase of intelligent robots increased by over 200%. This reflects a" increasing demand that was forcasted. In 1980 the demand for all types of robots was about 20K units. This is estimated to increase to 68K units by 1985 and to 115k units by 1990. The corresponding demands for intelligent robots about tripples each reporting period. But so much for Japan. Let's see how this compares to the US. In 1980 Japan had produced 3,200 units with a total value of 180M$ while the US had produced 1,300 units with a value of 100M$. At the end of 1980, Japan had 11,200 robots installed and- operating while the US had 4,400. But the gap is begining to narrow. There are also some interesting labor statistics. In Japan, the average labor cost per person has steadily increased from about ¥1,000 in 1970 to ¥3,000 in 1978. Over the same period of time, the average price of robots has remained about the same: ¥5,000 for all (Japanese, definition) robots and ¥12,000 for playback type robots. Thus the ratio of labor cost to robot cost has been decreased about 1/3. The actual value was about 3.7 in 1976 for playback robots. Superfically, a playback robot could be amortized within four years on a single shift. But the actual expenses of installation and maintenance resulted in a slower rate of amortization. In the future, labor costs are expected to rise 5 to 10% annually while robot costs will remain about steady. A summary of responses to a questionaire distributed by JIRA listed the order of importance for installing an industrial robot as

1. Economic advantage
2. Increased worker saftey
3. Unaiversalization of production
4. Stable product quality
5. Labor shortage

Hence, the economic advantage of the industrial robot over human labor, which seems certain to grow in the future, is considered as the most important factor in the increased application of industrial robots.

APPLICATIONS

In a broad sense, robots may be classified by the industry in which they are used. Statistically, about 30% of the robots have been used in the automobile industry from 1974 to 1.980. Over the same time, their use in the electrical applicance industry has increased from 10% to over 35%. The metal products industry show a less significant increase from 6% to 9% while use in the machinery industry has remained constant at about 5%. Another way of classifying robots is by application. In 1980 spot welding accounted for 57% and arc welding for 19% of all robots. The next leading application Was spray painting at 11%. All other applications accounted for 13%.

In Japan, by the end of 1980, Nissan was the largest user of spot "elders (300). At the same time, Toyota reported 200 spot welders. Kawasaki Heavy Industries is the leader in production of Unimations. Mitsubishi Heavy Industries occupied second place producing 10 per month. Other runner ups were Toshiba Seiki and Toyoda Machine Works. For arc welding a much lighter weight robot may be used. This market is presently dominated by Yaskawa Electric Manufacturing with a relatively low priced playback robot. Shinmeiwa has developed a" arc welder for heavy plate3 and Osaka Transformer has developed an arc welder for sheet metal. Koebe Steel has produced a "ore expensive, continuous path control, arc welder. Hitachi has a 10" priced articulated playback robot and Matsushits is entering the market.

Painting robots are the third largest type of playback machines and are now increasing in number at the same rate as welding robots. A person requires 2 to 3 years Of experience to become a skilled manual coating worker. However, the poor working environment and the tendency to be a more educated society has contributed to a developing shortage of skilled manual workers. This shortage is being filled by robots. Their use also saves 10 to 20% of paint. Koebe Steel has introduced the Norwegian Trallfa spray painting robot. Both Hitachi and Mitsubishi Heavy

Industries have worked with Nihon Parkerizing Company and Iwata Air Compressor Manufacturing, respectively, to develop playback spray robots. Tokico produces a large variety of low priced painting robots while Nachi Fujikoshi offers a spray robot with both remote and direct teaching.

Industrial robots have been applied to a wide variety of machine loading applications such as die casting, forging, press work and machine tool handling. In press working Aida Engineering seems to dominate the area but it is being strongly challanged by Toshiba Seiki. Similiar, Fusjitsu Fanuc is leading over Kawasaki Heavy Industries in the area of loading machine tools, Ichikoh Engineering Company, Ichikoh and Kyoshin Electric offer a complete line of fixed sequence machines. Star Seiki, Shoku and Daido offer both fixed and variable sequence robots. Shinko Electric has a relatively sophisticated variable sequence robot for putting workpieces into a furnace. Nachi Fujikoshi offer a robot specially designed to tolerte hot temperatures that finds application in transfering workpieces from a furnace to a press.

Fujsitsu Fanuc's robot is usually found working with NC machines. Their Model Ø uses the NC of the single machine tool which it services, while their Models 1, 2 and 3 have their own NC and service from two to five machines. These machines make possible an unattended system that operates automatically at night. Okuma, Yamatke-Honeywell and Ikegami Iron Works have also started producing robots for use with their NC machines.

Closely allied to machine loaders are the robots that simply transfer material form one place to another. Thus, Shinko Electric, Taiyo and Kayaba Industry have entered this field. conveyor manufacturers that also have transfer robots include Tsubakimoto and Sanki Engineering. Others are Kawasaki, that has a modified Unimate, Daido Steel, Yaskawa, Nachi Fujikoshi and Toyoda Machine. Dainichi Kiko has developed a line of heavy transfer robots. Togo Keiki has developed a series of variable sequence robots specifically dedicated to palletizing.

Assembly robots, capable of inserting, screw driving, bonding, etc exist largely in the early application stage. Most major electrical manufacturers such as Hitachi, Matsushita, Mitsubishi, Oki and Fujitsu have developed fully automatic systems for bonding. All of these use cameras for visual perception to position by shape or pattern and to detect defects (Mitsubishi). Hitachi manufacturers an intelligent robot with a 25 step memory and a 200 gm load capacity that can fit together different components, one-by-one, in a specified order. The larger electronic manufacturers are planning to robotize 50 to 75% of their assembly operations by 1985.

Supporting this type industrial development both in Japan and in the US is a wide range of university research; let me describe the US involvement. The principal universities are Stanford, MIT, Carnegie-Mellon, Rhode Island, Flordia, Purdue, Massachussets, Maryland, Rochester, Rensseler Polytech, Arizona, Wisconsin, Ohio state and others. The robotics research at Stanford University is long standing. Tom Binford did pioneering work in three dimensional vision. His students have developed a" advanced robot programming language, called AL (Arm Language). Their artificial intelligence laboratory has produced a list of ground breaking research projects in manipulation, hand-eye coordination, and assembly. Danny Hillis and John Hollerback of MIT are building robot skin that detects pressure to give a sense of touch. MIT is also active in robot vision and programming languages. Carnegie-Mellon University has programs in flexible assembly, mobility and intelligent robots. John Birk of Rhode Island University has developed robots with vision to acquire, Orient and transport pieces. One of their robots was the first to pick parts out of a bin of random oriented parts. They are also working on dexterous robot grippers and programming languages. Del Tessasr at the University of Flordia is working on teleoperators, force feedback and the kinematics/dynamics of robotic motion. Purdue University is working on robot control systems, programming languages, vision, and modeling part-flow through industrial plants. The University of Massachusetts is working on the visual interpretation of natural scenes and the design of parts for automatic assembly. The University of Maryland has a Computer Vision Laboratory. Herb Voelcker at the University of Rochester is developing advanced methods of representing three dimensional shapes in a computer memory. From this work a computer graphics language called PADL was developed. Herb Freeman at Rensselear Polytech Institute is studying the generation of computer models for three-dimensional curved surface objects. The University of Arizona is doing teleoperator work and the University of Wisconsin is doing work in machine vision. Robert McGhee at Ohio State University is working on dynamics and control of industrial manipulators and legged locomotion systems.

There are also many non profit and private industrial laboratories performing research in robotics. C. S. Draper Laboratories are working on machine vision for recognition and inspection. G. M. Research Laboratories has a unique method for obtaining silhouette immages of parts on a conveyor system. GE has a substantial robot demonstration facility. Westinghouse has established a robotic research laboratory. IBM has developed AUTOPASS and EMILY programming languages for robots. Texas Instruments is using robots for assembly and testing of hand calculators. Machine Intelligence Corporation, in coorperation with Unimation developed the first commercially available seeing robot. Unimation is working on control systems, calibration techniques, mobility and programming techniques. Cincinnati Milicron is also working on programming languages, control system architecture and mechanical design. Other manufacturers are Prab-Versatran, Autoplace, Advanced Robotics, DeVilbiss, Mobot, Nordson, Thermwood, ASEA, KUKA, Trallfa and US Robots as well as a dozen other smaller companies. Western Europeans are estimated to be spending from two to four times as much as the US in robotic research. Fiat, Renault, Olivetti and Volkswagan all have developed their own robots. The fact is, US robotics efforts are neither better funded nor better organized than those of our overseas trading partners.

PROBLEM AREAS

One of the first problems is accuracy (not repeatability). Robot positioning accuracy needs to be improved. Although repeatability of most robots is on the order of 0.05 inch over its working volume (and in Some cases as good as 0.005 inch), the absolute positioning accuracy may be off as much as 0.5 inch. Thus it is not now possible, without extensive calibration, for a robot to go to a" arbitrary mathematically defined point in coordinate space and have any assurance that the robot will come closer than half-an-inch. Presumably, this accuracy problem could be solved by applying closer manufacturing tolerances to the robot. Today, the solution is calibration or using the teaching method. However, no efficient method of robot calibration has been developed. Also, robot control software is not presently designed to use calibration. Thus, using a robot for Small lot batch assembly remains uneconomical.

Second, dynamic performance must be improved. Present day robots are too slow and clumsy to effectively compete with human labor in Assembly. Two execptions to this are arc welding, where a heavy welding gun must be moved through a string of points in space, a task which the robot does very well. However, if robots are to perform other types of assembly and construction tasks, they must be able to execute much more complex routines with greater speed and dexterity. Control systems need to be alternately Stiff and compliant along different axes in space. This requires much more sophisticated cross-coupled servo control computations than are presently employed.

Third, most robots can lift only about one-tenth of their own weight. Light weight construction is needed. Advanced control systems that can take advantage of such light weight structures and high speeds are a major research project.

Fourth, is the design of grippers that presently have only one degree of freedom. contrast this with the hmuman hand that has five fingers, each with four degrees of freedom. No robot has come close to duplicating the dexterity of the human hand! The problem is not so much in building such a mechanical structure, but in controlling it.

Fifth, sensors of many different types must be developed. Robots must be able to see, feel, and sense the position of objects in a number of dfferent ways. Processing of visual diata must become faster and be able to determine three-dimensional shapes and relationships. Robot grippers must both feel the presence of objects and sense the forces developed on these objects. Proximity sensors are needed on robot finger tips to enable the robot, to measure the final few millimeters before contacting objects. Longer range proximity sensors are needed on the robot arm to avoid colliding with unexpected obstacles. A variety of acoustic, electromagnetic, optical, x-ray and particle detectors are needed to sensethe presence of various materials such as metals, ferromagnetics, plastics, fluids,and limp goods, and to detect various types of flaws in parts and assemblies. Both the sensing devices and the software for analyzing sensory data represent research and developement problems of enormous magnitude.

Sixth, control systems are needed that can simultaneously take advantage of sophisticated sensory data from a large nember of different types of sensors. Present control systems are severely limited in their ability to modify a robot's behavior in response to sensed conditions. sensory data used in tight servo loops for high speed or precise motions must be processed and introduced into the control systems with delays of no more than a few milliseconds. Sensory data used for detecting the position and orientation of objects to be approached must be available within hundreds of milliseconds. Control systems that are properly organized in a hierarchical fashion (so that they can accomplish a variety of sensory delays of this type) are not available on any commercial robot.

Seventh, robot control systems need to have a much more sophisticated internal model of the environment in which they work. They must know three-dimensional relationships of both workplace and workpiece. These data are needed to generate expectations as to what parts should look like to the vision system, or what they should feel like to the touch sensors, or where hidden or occluded features are located. Eventually, such internal models might be used in the automatic generation of robot software by describing how a finished assembly should look, or even how each stage of a" assembly or construction task should appear in sequence.

Eighth, techniques for developing robot software must be vastly improved. Programming by teaching is impractical for small lot production, especially for complex tasks where sensory interaction is involved. Eventually, it will be necessary to have a whole range of programming languages and debugging tools at each level of the sensory-control hierarchy. Shop floor personnel, unskilled with computers, must be able to instruct robots in what to do and what to look for in the making sensory decisions.

Lastly, many potential robot applications require robot mobility. Most robots today are bolted to the floor or table top, or are hung from the ceiling. Small robots can reach only a few inches; larger robots only a few feet. But many applications need robots that can maneuver over much larger distances. For example, a robot used to load a machine tool typically spends most of its time waiting for the machine to finish its operations. Sometimes a single robot can be positioned between two or more machine tools so that it can be more fully utilized. Other times it can be mounted on a" overhead gantry traveling on rails in order to gain access to many machines. Unfortunately, to date this has prove" too expensive and clumbersome for wide scale use. I" many applications, like welding or painting large structures such as ships and aircraft, it is not practical to bring the work to the robot; the robot must go to the work. A good ship building robot should be able to maneuver inside odd shaped compartments, climb over ribs and bulkheads, scale the side of a ship's hull, and weld Seams several hundred feet in length. Similar mobility is required in the construction of buildings. I" some cases robots will need to climb stairs and work from scaffolding. Robots will also be used in undersea explorations, drilling and mining. Both of these developmenta will require significant new developments in mobility mechanisms. It may be possible to improve the mechanical accuracy of robots, and to improve servo performance with little more than careful engineering. But, much more fundamental research and development will be required before the sensor, control, internal modeling, generation, systems interface and mobility problems are solved. Much remains to be done in sensory technology to improve the performance, reliability and cost effectiveness of all types of sensory transducers. Even more remains to be done in improving the speed and sophistication of sensory processing algorithms and special purpose hardware for recognizing features and analyzing patterns in both space and time. Sensory interactive control systems, that can respond to various kinds of data at many different levels of abstraction, are still very much in the research phase. Current commercial robot control systems do not even allow real-time six-axis incremental movements in response to sensory data. None have convenient interfaces by means of which sensory data of many different kinds can be introduced into the Servo loops on a millisecond time scale for true real-time sensory interaction. None of the commercial robot control systems have anything approximating CAD data bases or computer graphics models of the environment and workpieces. Finally, current programming techniques are time consuming and not capable of dealing with internal knowledge or sophisticated sensory interactions. These are very complex problems that require many person-years of research. Is it not surprising that robot applications are still very limited?

It is often felt that standards are an inhibiting influence on a newly developing field because they impede innovation and stifle competition. In fact, just the opposite is true. Well chosen standards promote technology development and transfer. They make it posssible for ❑ S"y different manufacturers to produce various components of modular systems. Standard interfaces assure that multi-vendor systems will fit together and operate correctly. Individual modules can then be optimized and upgraded without making the whole system obsolete. They make it possible for a large number of robots, machine tools, sensors, and control computers to be connected together in integrated systems.

THE FUTURE

I" the future, you can expect that the problem area of today that I have just described will be solved. The industrial robot is still in it3 infancy. During the next decade I fully expect it will bloom into adulthood. Intelligent robots are representative of the leading edge of technology products. The growth of the industrial robot industry will bear eloquent testimony to state-of-the-art technology.

All of our problems are amenable to solution. It is only a matter of time and expenditure of resources before sensors and control systems are developed that can produce dexterous, graceful, skilled behavior in robots. eventually, robots will be able to store and recall knowledge about the world that will enable them to behave intelligently and even to show a measure of insignt regarding the spatial and temporal relationships inherent in the workplace. There is no question that given enough time and resources, robotics will eventually become a significant factor for increasing productivity in industrial manufacturing. The only question really is: How much time and resources will be expended before our desires become reality? In my opinion, more than a few tens of millions, and less than a few hundreds of millions of dollars will be required for R&D to make robots capable of performing a sufficient number of tasks to make significant productivity improvements. More that a few humdred and less than a few thousand person-years of high level scientific eand engineering talent will be needed. I" other words, a national R&D effort of at least one, and perhaps two,. orders of magnitude greater than what has bee" done to date will be required to succeed in this quest. And more than just total dollars spent is important. Robotics research is systems research. At least a few stable, consistantly well funded research centers of excellence will be required. It is a challanging and a" adventurous quest, a quest in search of today's solutions to yesterday's problems for increased productivity tomorrow. I hope you will join me in this quest!

MEASUREMENT ASSURANCE IN YOUR OWN LABORATORY

Rolf B. F. Schumacher
Rockwell International Corporation
Anaheim, CA

ABSTRACT

Measurement assurance is the application of broad quality control principles to measurements and calibrations. This paper demonstrates how quality control methods can be used to control the accuracies of measurements and calibrations.

CONTROLLING A PROCESS

In order to manufacture a number of like products efficiently, a manufacturing process must be established that consistently turns out the product with the desired characteristics at a predetermined cost. Once the process is established, one task of quality control is to keep it operating at the intended levels of product quality and production cost. Inadvertent changes in the process must not be permitted to occur; and if such changes do occur, steps must be taken to prevent their recurrence. To this end, numerous production control techniques have been invented which can also be used to control measurement and calibration processes. Ever since Eisenhart (Ref. 1) has shown that a measurement process, to yield measurements with known limits of variability, must behave like a production process which is in a state of statistical control, it has become very useful to consider a measurement process like a production process and apply to the measurement process controls similar to those first used to control manufacturing processes.

THE CONTROL CHART

One such control instrument is the control chart. In this paper, we shall examine how control charts can be used to control a measurement process. The word "measurement" is used here in a broad sense so as to include calibrations. In fact, the methods described here have primarily been used to control calibration processes.

The most widespread use of control charts in controlling measurement processes is in connection with the use of a check standard. To control a measurement process, a check standard is measured from time to time by the process to be controlled and its measured value entered on the chart. If more than one observation is normally made to determine a measured value, the dispersion of the observations is also determined numerically and can be entered on an accompanying chart to furnish an additonal control element.

As an example, refer to Figure 1, the control chart of a 1-ohm standard resistor used as a check standard for resistance measurements made by the same process. Figure 1 illustractes the simplest form of a control chart; other forms of control charts, yielding more or different information, will be introduced later.

In Figure 1, each point, X_i (i = 1, 2, 3...), represents one resistance measurement which, in this case, consists of one observation only. The center line is the average of the measurements and is indicative of the value towards which our measurement process of the resistor tends, in our case 1.000 012 3 ohms. (This value may be used as our best estimate of the true value of the resistor or it may be used to compare our measurement process with that of a higher echelon laboratory. If, for instance, the charted resistor has been certified by the National Bureau of Standards to a value of 1.000 009 5 ohms with an uncertainty of 2 microohms, the difference points to a possible systematic error in our measurement process or a changed value of the resistor or both.)

The dashed lines in Figure 1 are upper and lower control limits. They are usually drawn at three standard deviations (3-sigma) so that 99.73 percent of all measurements would theoretically fall within those limits, provided the measured values plotted come from a normally distributed population. Thus, a point falling outside these limits is always highly suspect of coming from a different population, suggesting a change in the measurement process or in the resistor, or revealing some operator error. Such an occurrence should be investigated immediately to determine the error cause and to correct the measurement value.

The equation for upper and lower control limits then is

$$L_U, L_L = \overline{X} \pm z\sigma \qquad (1)$$

where Z=3 for three-sigma limits and X is the average of all plotted points X_i.

The standard deviation of the measurement process is either known (a) from past experience or it is estimated (s) from the plotted points using equation 2.

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2}{n-1}} \qquad (2)$$

The first expression for s represents the definition of the term and is widely used to calculate s. The right hand expression for s is more easy to use in manual and calculator computations and gives certain advantages in computer calculations. Since s is a function of a small difference between two large numbers, different results may be obtained at times when calculating s with one or the other of the two expressions of equation 2 because of the effect of rounding. To avoid such differences, it is advisable to use as each value of X_i only the variable part of Xi in the calulation of s. For example, if X_1 = 1004, X2 = 1006, X3 = 995, etc., useas X_i Only 4, 6, -5, etc.

The term $\left(\sum_{i=1}^{n} X_i\right)^2$ stands here for the sum of all n measured values of X, squared after summation:

$$\left(\sum_{i=1}^{n} X_i\right)^2 = (X_1 + x2 + \ldots X_n)^2$$

And $\sum_{i-1}^{n} X_i^2$ stands for the sum of all squared values of x,

$$\sum_{i=1}^{n} X_i^2 = X_1^2 + X_2^2 + \ldots X_n^2.$$

If equation 2 is used to estimate the standard deviation of the n plotted points X_i, s replaces sigma (σ) in equation 1. Simultaneously, the factor Z must be replaced by Student's t which makes allowance for the limited number of data from which the estimate of sigma is derived, because Z aoolies strictlv only when the standard deviation is computed from a very large number of data points. Hence, for a limited number of points, equation 1 becomes

$$L_U, L_L = X \pm s\, t_{P,n-1} \qquad (3)$$

where $t_{P\ n-1}$ is the two-sided P-probability value for' Student's t for n-l degrees of freedom. For upper and lower control limits, $t_{0.9973}$ (corresponding to the normal deviate Z = 3.0) or $t_{0.995}$ are recommended. When the number n of al 1 points Xi is small, the equivalent of two-sigma control limits is often used; in such cases, $t_{0.9544}$ (corresponding to the normal deviate Z = 2.0) or $t_{0.95}$ is applied at the slightly increased risk of rejecting erroneously a perfectly valid measurement value falling outside the control limits. Many textbooks contain tables of Student's t factors for various values of P and various degrees of freedom (in this case, n-l). However, we owe to Brian Joiner (Ref. 3) the calculation of t factors corresponding to whole numbers of Z. Table I lists some values of t.

The distance of the control limits from the center line (X) either calculated from multiplying the known standard deviation by three or from equation 3, represents also the limits of the random error of the charted measuring process. To this random error, we simply need to add the known or estimated limits of systematic error to arrive at the <u>total uncertanty limits of the measuring process</u>.

When the standard deviation of the measuring process is known and some points repeatedly fall outside the control limits, the process is out of control and should not be used for measurements before the causes for the out-of-control condition have been removed. Such a change in the measuring process, however, may also require a re-evaluation of the random error of the measuring process.

An important condition for the use of control charts is that the measurement process remains the same throughtout. Different measurement processes require separate control charts. Thus, a control chart monitors the entire measurement process, in our example the resistor and the system measuring it. In fact, a control chart for a standard resistor will show an out-of-control situation developing when for instance the oil of the bath in which it is kept loses its insulating qualities, eve" though the resistor and the other parts of the measuring system have remained stable.

The control chart can yield considerably more information, however, In addition to identifying a measurement with a likely excessive error, it can signal promptly a slightly changed measurement process, even though individual measurements may still lie within the expected uncertainty band. For this reason, frequently oneand two-sigma lines are drawn on the chart between the control limits as shown in Figure 2. With known standard deviation (sigma), the band between a control limit and the center line is simply divided into three equal parts. When the standard deviation is estimated as in equation 2, one- and two-sigma equivalent lines are drawn using equation 3 and $t_{0.6826}$ and $t_{0.9544}$ respectively or, if these t-factors are unavailable, $t_{0.70}$ and $t_{0.95}$.

With one and two-sigma lines we can spot a bias which did not exist before, a developing out-of-control condition, or a changed systematic error, when

a. two out of three successive points fall beyond the two-sigma line,
b. four out of five successive points fall beyond the one-sigma line, or

c. eight successive points fall an one side of the center line.

The measurement process should be investigated for a probable cause changing the results of the measurements when one of the above conditions has occurred, because conditions a, b, and c have only a 0.16%, 0.32%, or 0.4% chance of occurring when the measurements are normally distributed.

TREND CHARTS - CONTROL CHARTS FOR REFERENCE STANDARDS

Stable Standards

Control charts for reference standards are also called Trend Charts. They are an indispensable tool to

1. assign a best value to a measurement standard and thus prevent a laboratory from making the common mistake of always assigning to the standard the latest value reported by the higher echelon calibration laboratory (e.g., NBS);

2. estimate the total uncertainty of the standard (which is in most cases larger than the calibration uncertainty reported by the higher echelon laboratory) and thus avoid another common oversight;

3. indicate the relative stability or drift (trend) of the standard or, when only a few points are available, give the metrologist some indication of what behavior he might expect of it in the future and, therefore, help to

4. determine the date when the reference standard will have to be recalibrated or recertified.

They thus furnish the key to a wealth of information embodied in seasoned reference standards that would otherwise be disregarded and remained locked into them were it not for Trend Charts.

In fact, a laboratory which assigns to its standards the value obtained from the latest calibration of that standard introduces in most cases an out-of-control condition into their measuring system while considerably underestimating the uncertainty of their standard.

As an example, consider the Trend Chart of a one-ohm standard resistor, Figure 3. All values were reported to us by the National Bureau of Standards (NBS) as the mean of two observations each with a known standard devation of random error of approximately 0.2 microohms. The standard deviation of each mean of two measurements, therefore, is calculated to be

$$\frac{\sigma}{\sqrt{n}} = \frac{0.2}{\sqrt{2}} = 0.14 \text{ microohms.}$$

Control limits drawn at three standard deviations of NBS's random error would, therefore, fall about 0.4 microohms from the center of trend line, excluding most of the points. Such a control chart would show a process that is out-of-control -- which is certainly not the case. But we know that the standard probably undergoes small changes over long periods and may be influenced by additional short-term fluctuations. There is, of course, also the non-negligible probability that NBS's systematic error changes somewhat over longer periods. In sum, the uncertainty of the value of the standard is generally larger than the uncertainty of the value reported by the calibrating laboratory. All the sources contributing to the apparent fluctuations of the standard's value over longer periods whose causes are not identifiable, including the random error of NBS's measurements, can be considered as belonging to one cause system. We can, therefore, estimate the magnitude of the combined effects causing the random fluctuations between calibrations from equation 2.

The estimate of the standard deviation of the first five points ($n_1 = 5$) calcualted from equation 2 is sl = 0.518 microohms. Since only five points were available, two-sigma limits were drawn at 1.5 microohms from the center line. These limits should be considered as limiting the band within which all expected future values should fall if the standard remains stable and the sources causing the variability do not change.

The best known value of the resistor, in the absence of any discernible drift, is the average of the recorded values, provided we have no reason to discard any of them. Beginning January 1965, the value to be assigned to the standard plotted in Figure 3 was 1.000 013 44 ohms. In April 1967, recalibration of the standard yielded a value of 1.000 013 6 ohms requiring only an insignficant change of the value assigned to the standard of 1.000 013 47 ohms as shown in Figure 3. The additional point permitted also the narrowing of the two-sigma equivalent control limits to 1.2 microohms as n had now increased to 6 ($n_2 = 6$).

Having determined 1.) the value to be assigned to the standard after its calibration in April 1967 (1.000 013 47 ohms) until its next calibration and 2.) the range of values in which future calibrated values will be expected to lie, we must now calculate the uncertainty limits about the assigned value in accordance with equation 4:

$$L_U, L_L = \bar{X} \pm \frac{s}{\sqrt{n}} t_{P,\, n-1} \qquad (4)$$

For the first five values, the limits of uncertainty are at 1.000 013 44 ohms to.66 microhms, $t_{0.9544,4} = 2.869$. After April 1967, the uncertainty limits about the assigned value are at 1.000 013 47 ohms ±0.51 microohms, $t_{0.9544,5} = 2.649$. These limits include the effects of all experienced sources of variability on the value of the standard and should be considered the uncertainty due to random fluctuations of $\bar{X}$.

To arrive at the total uncertainty with which the value of the standard is known to us, we now only have to add the systematic error of the reported value to the uncertainty due to random fluctuations calculated above in equation 4. In our case (Figure 3), the systematic error for the period 1963 through 1969 was reported to be about 0.5 microohms maximum, so that the total uncertainty of the value of 1.000 013 4 ohms, assigned to it in 1965, was about 1.2 microohms (0.66 + 0.5 microohms). This total uncertainty dropped in 1967 to 0.51 + 0.5 = 1.0 microohms.

Although the 0.5 microhms maximum limits on the systematic error may already include some variable component which then would also be included in the uncertainty limits plotted on the control chart, nothing is known about its magnitude, so that prudence dictates that we add the entire systematic error component of NBS to our Uncertainty.

As time progresses, trend charts must sometimes be updated to account for changing technology in calibrating the standard, changing measurement techniques, a perhaps slowly changing standard itself, and sometimes changing definitions. Such Updating can be accomplished for instance by dropping some of the earliest values or by assigning different weights to the values, with the higher weights being assigned to the latest values and low weights to early values. If, for instance, the standardizing laboratory (e.g., NBS) utilizes calibration techniques yielding significantly narrower limits of uncertainty than before, it may be appropriate to weigh the charted values with a factor inversely proportional to the reported uncertainty limits.

Standards with Observed Drift

A bit more complicated is the construction of a control chart for standards with an observed drift. If the drift is approximately linear, the best known value of the standard, X, at any time t may be expressed by equation 5.

$$X = \hat{b} + \hat{m}\, t \qquad (5)$$

where $\hat{b}$ is the least squares X-intercept and $\hat{m}$ is the least squares slope.

$$\hat{m} = \frac{\sum_{i=1}^{n} X_i t_i - \bar{X} \sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} t_i^2 - \bar{t} \sum_{i=1}^{n} t_i} \quad ; \quad \hat{b} = \bar{X} - \hat{m}\bar{t} \qquad (6)$$

the symbols $\bar{t}$ and $\bar{X}$ represent average t and X-coordinates

$$\bar{t} = \frac{1}{n} \sum_{i=1}^{n} t_i \qquad \bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \qquad (7)$$

Refer to Figure 5, the trend chart of a gage block suspected to be shrinking gradually after a control chart was plotted and long before any reason for such a shrinkage could be found. The chart was plotted in March 1965 on the basis of five successively reported values. The X indicates a value reported by NBS in April 1966.

To check whether the calculated least-squares line adequately describes the suspected drift, upper and lower control limits (dashed lines) are drawn (at 95 percent probability limits in Figure 5) at a distance dk from the trend line for selected past instances tk calculated from

$$d_k = t_{P,n-2}\, s_X \left[\frac{1}{n} + \frac{(t_k - \bar{t})^2}{\sum_{i=1}^{n} t_i^2 - \bar{t} \sum_{i=1}^{n} t_i} \right]^{1/2} \qquad (8)$$

where $t_{P,n-2}$ is the two-sided P-probability value of Student's t for n-2 degrees of freedom and s_X is the estimate of the standard deviation computed from

$$s_X^2 = \frac{1}{n-2} \left[\sum_{i=1}^{n} X_i^2 - \bar{X} \sum_{i=1}^{n} X_i - \frac{\left(\sum_{i=1}^{n} X_i t_i - \bar{t} \sum_{i=1}^{n} X_i \right)^2}{\sum_{i=1}^{n} t_i^2 - \bar{t} \sum_{i=1}^{n} t_i} \right] \qquad (9)$$

These control limits serve mainly to check the adequacy of our selected model. If a past paint, which we have established as being valid, falls outside these limits, we should re-examine our model; otherwise we accept it and use it to forecast future values of the standard and their associated limits of uncertainty. (It is assumed here that the uncertainty of the past point due to random variability is negligible with respect to dk.)

To determine the limits of uncertainty for projected future values of the standard (solid control limits in Figure 5), the distance df from the (solid) trend line at any future time t_f is calculated from

$$d_f = t_{P,n-2}\, s_X \left[1 + \frac{1}{n} + \frac{(t_f - \bar{t})^2}{\sum_{i=1}^{n} t_i^2 - \bar{t} \sum_{i=1}^{n} t_i} \right]^{1/2} \qquad (10)$$

The standard is recalibrated whenever the uncertainty about its assigned value, as indicated by the projected limits of uncertainty, becomes as wide as measurement requirements permit, unless other considerations make earlier recalibrations desirable. Whenever a new value is obtained, the trend chart, of course, is updated, trend lines, control limits and projected uncertainty limits are recalculated. Eventually it may also here become desirable to drop some of the oldest points. A decision to drop some old points should be based on identifiable differences between the older points and the later points or the processes by which they were obtained; it should not be made arbitrarily.

Higher order least squares curves with control limits are considerably more difficult to construct. And before embarking on such a project, it is advisable to determine first whether the additional information obtained from a higher order trend chart will be worth the cost. We should bear in mind that the number of degrees of freedom decreases with increasing order of the curve. When the number of points to be fitted is small, the uncertainty of any value on the least squares curve may not be significantly less than that obtained from a linear approximation.

CONTROLLING THE TOTAL MEASUREMENT PROCESS

The $\bar{X}$ and R-Chart

One of the most powerful tools to control the entire measurement process are control charts for averages and dispersions (Figure 6).

They can be constructed and maintained whenever one calibration or one measurement value is the average of more than one observation. For example, Figure 6 depicts the measurement process of l-ohm resistors where each measured value is the average of four observations made on a check standard measured with the same process as the unknown resistors. The observations are made over a period of 32 to 48 hours. The $\bar{X}$-Chart, the plot of the averages of four observations, is in all respects similar to the control charts shown in Figure 1 and 2, except for the calculations of the control limits. The comments made concerning the simple control charts, including the evaluation criteria, apply here as well.

But in addition to plotting the measured values, we also plot a measure of the dispersion of the four observations on which each average is based. For instance, the second point on the $\bar{X}$-Chart (Figure 6) is plotted as 1.000 012 25 ohms, this value being the average of three observations yielding 1.000 012 ohms and one yielding 1.000 013 ohms.

Beneath the 1.000 012 25 ohm point on the $\bar{X}$-Chart, we plot, therefore, the range of the measurements on the R-Chart, in this case 1 part per million. (The range is the algebraic difference between the largest and the smallest observation from those observations from which the plotted average was calculated.)

Instead of charting the range on an R-Chart, we could also plot the estimates of the standard deviation on an s-Chart. An s-Chart should be used when the number of observations of each point is large, say in excess of ten. But, "The R-Chart is preferred to the (s-Chart) because of its simplicity and versatility; and, unless there are compelling reasons to use the (s-Chart), the R-Chart is the method of choice" (Ref. 4, p. 2-7). "For small samples, the sample range is a reasonably efficient substitute for s as an estimator of the standard deviation of a normal population - not as efficient as s, but earier to calculate..." However, "As the sample size gets larger, the range is not only troublesome to calculate, but is a very inefficient estimator of σ" (Ref. 4, p. 2-7). The range should not be used as an estimator of the standard deviation for samples of more than ten observations (Ref. 5, p. 62).

The center line of the $\bar{X}$ Chart, $\bar{\bar{X}}$, is the (grand) average of the plotted averages. The center line of the R-Chart, $\bar{R}$, is the average of the plotted ranges. With at least ten points available, we enter a preliminary center line and upgrade it to a more permanent status when we have at least 25 points to base our averages on. Upper and lower control limits are drawn at three-sigma from the center line as shown below. (See also Ref. 5.)

We should bear in mind that we are plotting the results of pilot measurements, using a known check standard added to a number of unknown items to be measured, in order to control the quality (accuracy) of the process employed to measure the unknown items. From the verifiable results of measuring the known check standard we draw conclusions about the quality of our measurements of the unknown items.

Although occasionally a point may fall outside the control limits as a matter of pure chance, each time this happens the existence of some abnormality in the measurement is suspected, and the measurement is repeated. If the point of the repeat measurement also falls outside the control limits,, the existence of an abnormality is taken as being confirmed. The causes for this abnormality are then determined, removed, and the measurement is repeated. If the points on the $\bar{X}$ and the R-Chart fall within the control limits, the measurement is considered valid. Since our customers' unknown items are measured by the same process, their values thus determined are also considered valid.

The X-Chart will reveal the existence of short term trends or cycles, and unusual systematic errors. The R-Chart is predominantly an indicator of the precision of the measuring process, reflecting, among other things, the care of the operator and the control of the environment in which the measurement was performed.

Charts for the range (R-Charts) or the standard deviation can also be used to detect short-term instabilities of the measured items; such a case is illustrated in Ref. 2 (pp. 326-327) for the calibration of standard cells.

Since a control chart is the result of a compilation of a considerable amount of data concerning one measuring process, the average experienced range $\bar{R}$ can be used to determine the standard deviation of the measuring process. "Most experimental scientists have very good knowledge of the variability of their measurements, but hesitate to assume known σ without additional justification. Control charts can be used to provide the justification" Ref. 4, p. 18-Z).

Constructing and Evaluating the $\bar{X}$ and R-Chart

The recent grand average of pilot measurements illustrated in Figure 6 is $\bar{\bar{X}}$ = 1.000 012 3 ohms and the average range is $\bar{R}$ = 2.2 microohms as plotted. Upper and lower control limits on the X-Chart of the averages are at a distance of $A_2\bar{R}$ = 0.729 x 2.2 = 1.6 microohms from the grand average $\bar{\bar{X}}$. Upper and lower control limits of the R-Chart of ranges are at $D_4\bar{R}$ = 2.282 x 2.2 = 5.0 microohms and $D_3\bar{R}$ = 0 x 2.2 = 0.0 microohms respectively, as plotted. The estimated mean standard deviation of the calibration process, where each measured value is the average of n' observations (in our example n' = 4) and where the observations have an average range R is

$$\sigma_{\bar{X}} = \frac{\bar{R}}{d_2\sqrt{n'}} \qquad (11)$$

and the three-sigma control limits are at

$$3\sigma_{\bar{X}} = \frac{3\bar{R}}{2\sqrt{n'}} = \frac{3 \times 2.2}{2.059\sqrt{4}} = 1.6 \text{ microohms} = A_2\bar{R}$$

The factors A2, d_2, D3, and D_4 are tabulated in Ref. 4 and 5. See also Table 3.

Like all the others, these control charts also must be updated periodically after some new group of points have been entered to permit them to remain responsive to changes in the measurement process as it operates now and to determine whether some more hidden, long-term effects have changed the process. At that time it may also become desirable to drop some of the earlier points.

The check standard whose control chart we are keeping, as in Figures 1, 2, or 6, should be measured or calibrated occasionally by a different process, preferably with higher accuracy. It is then very likely that the value obtained by this process differs from the long-term average, $\bar{X}$ in Figure 6 or $\bar{X}$ in Figures 1 and 2, shown as the center line of our control chart. This may mean that our process converges to a value which is somewhat different from a value obtained elsewhere.

The check standard for the process depicted in Figure 6 is calibrated from time to time against the reference standard of the laboratory and is known to be 1.000 012 5 ohms in terms of the laboratory's reference, or 0.2 microohms larger than indicated by the control chart, Figure 6. We must now answer the important question: "Is this difference significant? Does the difference indicate a bias which should be corrected or can such a difference be accounted for by the variability of the process controlled by this check standard?

We answer this question by noting that the difference is statistically significant at a level α if it is larger than

$$u = z_p \frac{\sigma_{\bar{X}}}{\sqrt{n}} \qquad (12)$$

where z_p is the standard normal variable or the ordinate of the normal curve for a two-sided P probability value where P = 1-n. From (11)

$$\sigma_{\bar{X}} = \frac{2.2}{2.059\sqrt{4}} \doteq 0.534 \text{ microohms}$$

and from (12)

$$u = 1.96\frac{0.534}{\sqrt{17}} \doteq 0.25 \text{ microohms}$$

Since our difference of 0.2 microohms is less than u, we conclude that the difference is not significant at the 5% level. Otherwise we would have to conclude that our process may have developed a bias which we would have to eliminate before using the process for further measurements.

THE "BOTTOM LINE"

The total uncertainty of the process illustrated by the above example is then the sum of the random error and the systematic error. For measurements in sets of four, the random error of our process is 1.6 microohms from Figure 5 and the above calculations.

The systematic error is composed of the total uncertainty of the standard plus any systematic uncertainty contributed by the transfer process. From the above calculation, we have no reason to suspect any systematic uncertainty contribution from the process, so that the total systematic error is the uncertainty of the standard. The standard is the one whose trend chart is shown in Figure 3. We calculated its total uncertainty in 1967 as 1.0 micraohms, Hence, we should report the total uncertainty of the measurement as 2.6 microohms, consisting of a process random error of 1.6 microohms, using three standard deviations, plus a systematic error estimated not to exceed 1.0 microohms.

SURPRISES

Metrologists, attempting to obtain an objective measure of the uncertainties of their measurements by the methods illustrated here, frequently meet with surpises caused by "between-group" random error (Figure 7).

Depending under what conditions observations are repeated, some sources responsible for variations may not be included in the repetitions. Metrologists estimating the random error of their measurements from individual sets of observations would thus underestimate the uncertainty. In fact, <u>the neglect of possible between-group random errors is probably one of the single largest causes of underestimating uncertainties.</u>

$\bar{X}$ and R-Charts will signal the presence of unaccounted for between-group random errors. Since the ranges and the average range $\bar{R}$ depend only on the within-group random error, a chart constructed as outlined above under 'Controlling the Total Measurement Process" will indicate an out-of-control condition in accorance with the criteria described under "The Control Chart.". Such an indication is given if several points fall beyond the three-sigma control limits calculated and plotted as $A_2\bar{R}$, or too many points fall on one or the other side of one-sigma and two-sigma lines. (These lines should also be plotted on the control chart.)

If that happens, the origianl control limits as well as one-sigma and two-sigma lines should be discarded and new control limits calculated as shown for trend charts, using equation 4 and the method outlined under "Stable Standards."

Having thus been made aware of the presence of additional error sources between calibrations or measurements, we may investigate the origin of such additional error sources and, after eliminating them, increase the precision of the process. If, on the other hand, the process is deemed to be sufficiently precise, we may consider reducing the number of observations per measurement or calibration. Another recommendable alternative would be to redesign the process so as to include the previously excluded sources of variation. The object here is to make the process and the controls as efficient as possible.

CONCLUSION

Other control charts may be used for different purposes; other evaluation methods have been developed for specific measurement control purposes. For further studies of the subject, the reader is referred to the Bibliography. The control charts discussed here, however, are most valuable in assuring the validity of precision measurements and the quality of the services rendered by metrologists.

Unstable standards cause out-of-control measurement systems, regardless whether the instability is caused by a standard which actually changes or whether it is caused by us when we assign periodically different values to the same thing. Trend charts for reference standards will greatly enhance the stability of our standards by telling us what best values to assign to them; they will also tell us the combined uncertainty of the assigned value which is subject to short-term and longer-term fluctuations, i.e., the total uncertainty except for the systematic error. Control charts for check standards enable us to monitor continuously the quality of our measurement processes, give us an accurate indication of the variability of the measurement processes, indicate promptly when individual measurements had excessive random or systematic errors, and signal rapidly when measurement processes drift out of control.

With control charts we can greatly enhance the quality of our measurements at a small additional effort. And in some cases, control charts can give us assurance of accuracies that cannot be achieved by any other means at any cost.

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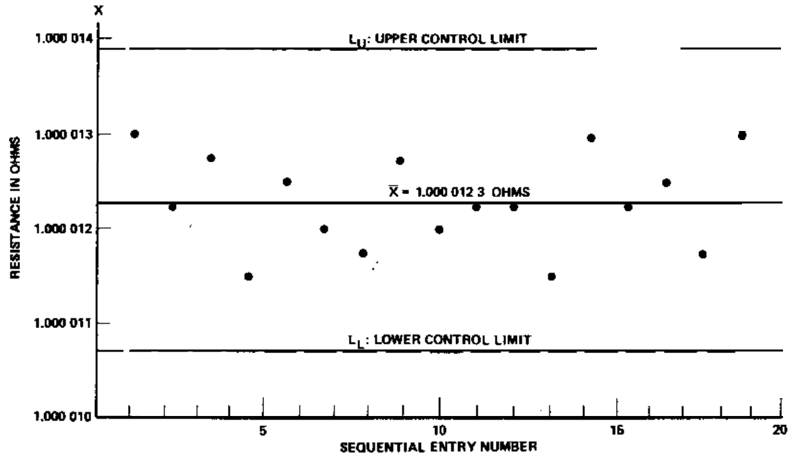
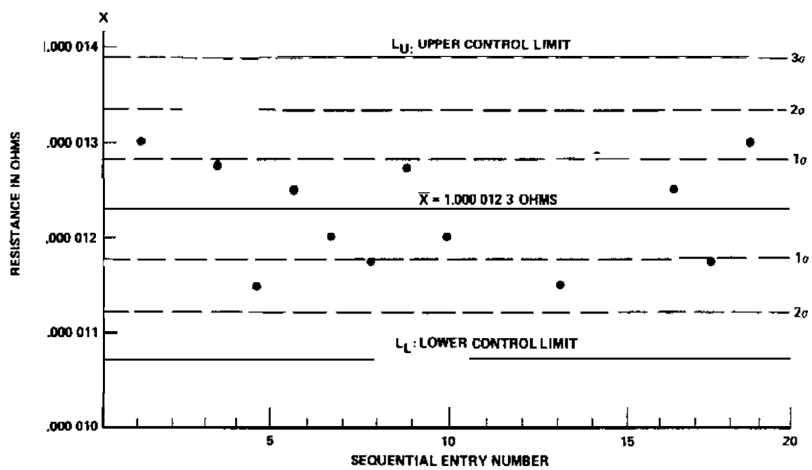
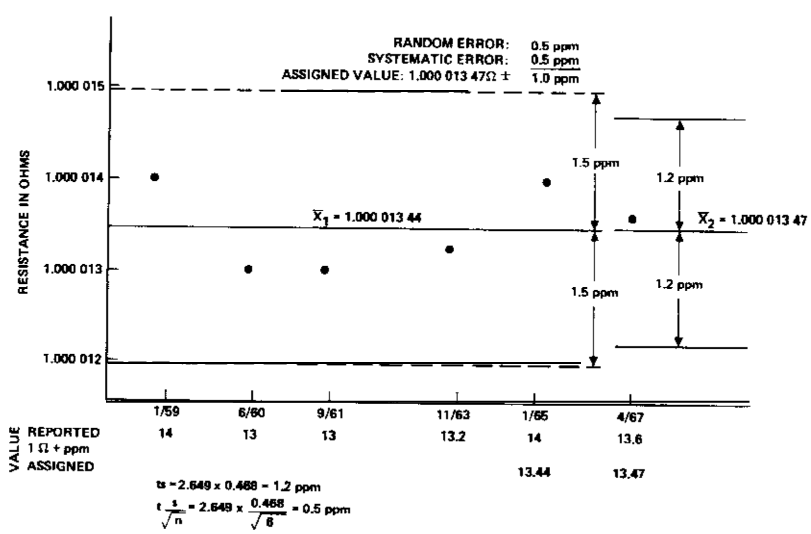


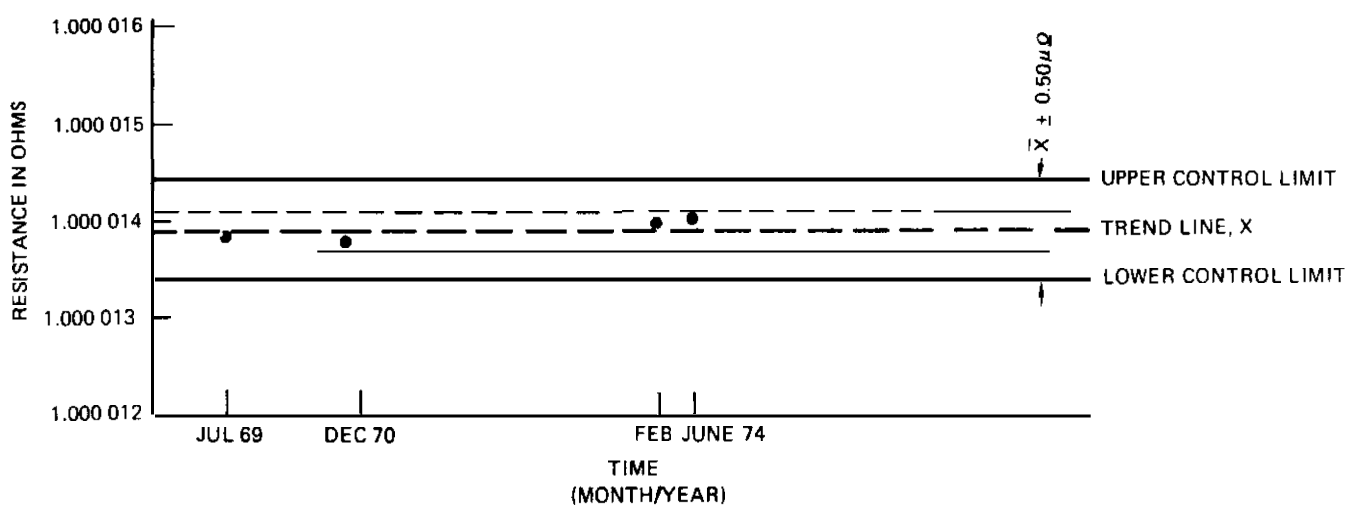
Control Chart of a One-Ohm Resistor Used as a Check Standard
Figure 1



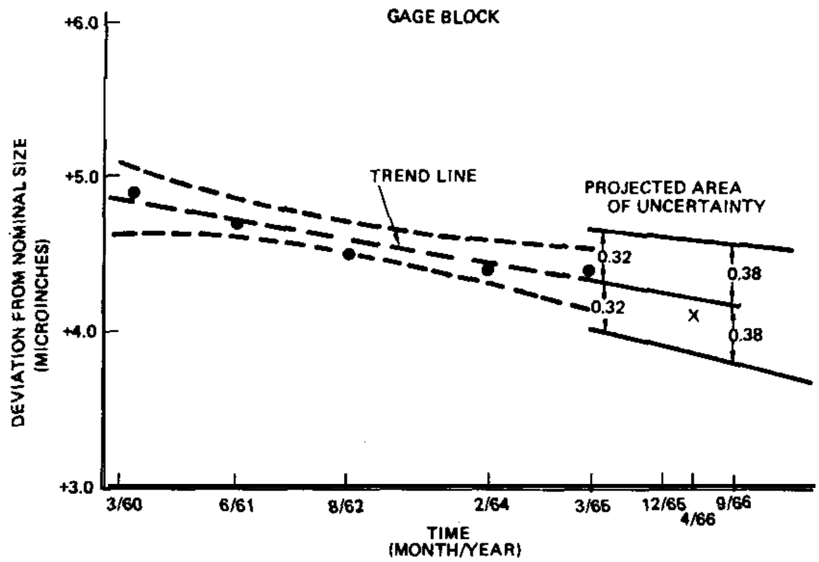
Control Chart with One-, Two-, and Three-Sigma Lines
Figure 2



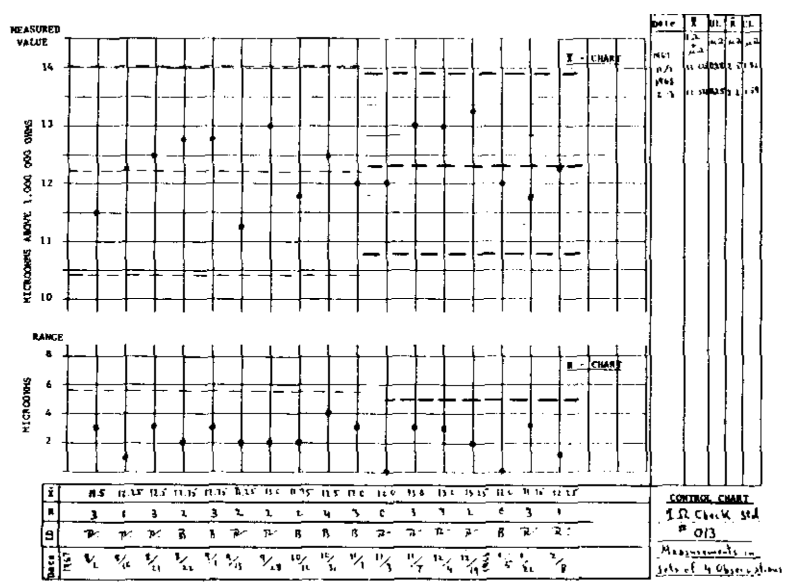
Trend Chart of a Thomas Type Standard Resistor
Figure 3



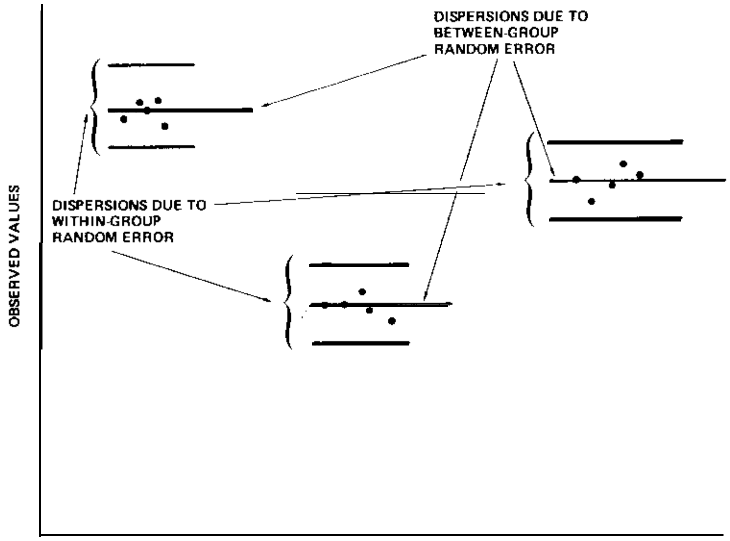
New Technology Requires Dropping of Old Data.
Updated Trend Chart of Standard Resistor.
Figure 4



Trend Chart of Gage Block
Figure 5



$\bar{X}$ and R Chart, Control Chart for Averages and Dispersions
Figure 6



Within-Group and Between-Group Random Error
Three Measurements, Each Based on Five Observations
Figure 7

TABLE I.
STUDENT'S t FACTOR $t_{P,v}$

Degrees of Freedom v	One-Sigma Equivalent P: 0.6826 *	0.9500	Two-Sigma Equivalent 0.9544 *	0.9900	0.9950	Three-Sigma Equivalent 0.9973 *
1	1.837	12.706	13.968	63.657	127.32	235.80
2	1.321	4.303	4.527	9.925	14.089	19.207
3	1.197	3.182	3.307	5.841	7.453	9.219
4	1.142	2.776	2.869	4.604	5.598	6.620
5	1.111	2.571	2.649	4.032	4.773	5.507
6	1.091	2.447	2.517	3.707	4.317	4.904
7	1.077	2.365	2.429	3.499	4.029	4.530
8	1.067	2.306	2.366	3.355	3.833	4.277
9	1.059	2.262	2.320	3.250	3.690	4.094
10	1.053	2.228	2.284	3.169	3.581	3.957
25	1.020	2.060	2.105	2.787	3.078	3.330
$\infty (z_p)$	1.000	1.960	2.000	2.576	2.807	3.000

*From Reference 3

TABLE II
EQUATIONS FOR CONTROL CHARTS

Chart	Center Line	Three-Sigma Control Limits: Upper	Three-Sigma Control Limits: Lower	Remarks
$\bar{X}$-Chart	$\bar{\bar{X}} = \frac{1}{n}\sum_{i=1}^{n} \bar{X}_i$	$\bar{\bar{X}}+A_2\bar{R}$	$\bar{\bar{X}}-A_2\bar{R}$	
		$\bar{\bar{X}}+A'_1\sigma$	$\bar{\bar{X}}-A'_1\sigma$	See Notes 1 and 2
R-Chart	$\bar{R} = \frac{1}{n}\sum_{i=1}^{n} R_i$	$D_4\bar{R}$	$D_3\bar{R}$	$\sigma = \frac{\bar{R}}{d_2}$
s-Chart	$\sigma = \bar{s} = \frac{1}{n}\sum_{i=1}^{n} s_i$	$B_4\sigma$	$B_3\sigma$	$s_i = \sqrt{\frac{1}{K-1}\left[\sum_{j=1}^{K} X_{ij}^2 - \bar{X}_i \sum X_{ij}\right]}$ See Note 2.

Note 1: $A'_1 = \sqrt{\frac{n-1}{n}}\, A_1$ where A_1 is as listed in Ref. 5

Note 2: Use only to control consistency of included data; not for comparison against prior data.

TABLE III
FACTORS FOR CONTROL CHARTS

Number of Observations in Sample, n	A'_1	A_2	B_3	B_4	D_3	D_4	d_2
2	2.659	1.880	0	3.267	0	3.267	1.128
3	1.955	1.023	0	2.568	0	2.575	1.693
4	1.628	0.729	0	2.266	0	2.282	2.059
5	1.428	0.577	0	2.089	0	2.115	2.326
6	1.287	0.483	0.030	1.970	0	2.004	2.534
7	1.182	0.419	0.118	1.882	0.076	1.924	2.704
8	1.099	0.373	0.185	1.815	0.136	1.864	2.847
9	1.031	0.337	0.239	1.761	0.184	1.816	2.970
10	0.975	0.308	0.284	1.716	0.223	1.777	3.078

APPLICATION OF GENERAL LINEAR MODELS TO CALIBRATION DATA

L. S. Mordecai
Navy Primary Standards Laboratory
Naval Air Rework Facility, North Island
San Diego, California 92135

ABSTRACT

Measurement processes and measurement systems exhibit variability which forms part of the limit on calibration accuracy. Standards laboratories often maintain separate records of in-house inter-comparisons and customer calibrations. If data from customer and in-house measurements all originate from a single, common measurement process, then inter-comparisons of both sets of standards can be included in one general linear model. The process of estimating the values of the standards and the variability of the measurement process can be both the single most powerful and the most convenient at the same time. This paper discusses the principle of general linear statistical models and their typical application to calibration data. Segments from typical basic language computer programs are included to demonstrate their implementation on desktop computers.

INTRODUCTION

This paper is written for the practicing metrologist who has had introductory courses in statistics and who is faced with the need to select the best tool for designing a measurement process, its data collection scheme, and its statistical algorithms. Our approach is to examine the often forgotten linear model. General linear statistical models possess a unique appeal since they permit fitting data in a least-squares sense to mathematical models of great intuitive value. The user can directly assess the effect of changes in measurement process design on the estimated measurement uncertainties. The user can also visualize the information available in the measurement design.

The first task is to decide which effects are truly important. It is tempting to attempt to test for a wide variety of effects. However additional data and measurement setups are costly. A carefully designed measurement (calibration) process will repay the thought that went into it. Careful design will include necessary checks between in-house standards and the values of the units under test. They may or may not consider right/left effects, time effects, interactions between standards, non-linearities of comparators, and myriad other effects. The best model to "se is the simplest; that which includes the important effects, and ignores the insignificant ones. We should not proceed to the subject of general linear models without agreeing with one another that a model may make no physical sense and still fit well mathematically.

THE GENERAL LINEAR MODEL

Calibration is the process of characterizing the relationship between observables and variables. For example the indication of an instrument in terms of a measured parameter might be of first order:

$$y = b_0 + b_1x_1 + e = \text{"true" (observations)} \qquad (1)$$

The instrument indication is x_1, b_0 and b_1 are constants and e is "noise."

There are several possible sources of measurement noise in the term e. One source is short range unrepeatability observed during a measurement run on a given day. Another source is the "process precision" observed over a longer period of time and across many hook-ups and experimental conditions. Finally there is noise due to poor fit between observations and the statistical (mathematical) model. This last noise component may be reduced by finding a better model such as the following:

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_kx_k + e \qquad (2)$$

This model shows that the observations are affected by k first order variables with linear coefficients. There are several common uses for this model in a standards laboratory. The first "se is during direct intercomparisons. Each of the k coefficients represents the inclusion or exclusion of the corresponding standard in the comparison. A comparison between two standards can be represented by setting their respective coefficients equal to 1 and -1 with all other coefficients set to zero.

Linear models are also used for curve fitting where observations are related to functions of variables. A good example of this is the fitting of data to power series in one or more variables. Thus each of the independent variables may be a term in a power series in the choice variable. Data may also be fit against trigonometric terms and other analytical functions which we do not have space to discuss in this paper. See Draper and Smith(1) for more information on regression analysis.

Both comparison calibrations and curve fitting calibrations can be supported analytically by the same algorithmic approach once the appropriate models have been set up. In addition, suspected interactions between variables can be estimated when observational data includes situations where the interacting variables have varied in all the possible combinations of variables. A simple two way model (two-way factorial) is:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_2 + e \qquad (3)$$

Large, complex statistical models are often self-defeating since they include minor effects which do not significantly reduce noise. The model should be the simplest one which reduces measurement noise to a residual.

LEAST SQUARE ERROR

The examples of general linear models discussed all included a noise term. The expectation value of that term is the pooled variance taught in intermediate statistics courses. The general linear model is thus seen to facilitate data pooling and reduction of measurement noise. This increases measurement process precision.

Returning to equation (2), the error between any one observation y and the "best fit" is given by:

$$e_i = y_i - bx_i \qquad (4a)$$

The estimate of the variance based on n measurements is:

$$s^2 = \frac{\sum_i (y_i - \sum b_j x_{ij})^2}{(n - k - 1)} \qquad (4b)$$

The set of b coefficients which minimizes the estimate of the pooled variance is called "best fit" coefficients for "least square error." Since the "best fit" linear statistical model reduces the estimate of the pooled variance to a minimum, the model serves to reduce noise at the observation points. The coefficients, which become the reported calibration values, are derived by a process which is both convenient and very efficient. The next task is to develop a generalized algorithm for computing best fit coefficients under the assumption that the data can be pooled validly.

The pooled variance is minimized by setting all partial derivatives of the variance with respect to the coefficients of equation (2) equal to zero.

$$\frac{\partial^2 s}{\partial b_0^2} = 0, \frac{\partial^2 s}{\partial b_1^2} = 0 \ldots\ldots, \frac{\partial^2 s}{\partial b_k^2} = 0 \qquad (5)$$

When we differentiate the terms of the polynomial model (equation (2)) as required by least squares fit criteria in equation (5), we end up with a set of algebraic equations known as the "normal equations." The normal equations for a polynomial model are:

$$b_0\sum x_0^2 + b_1\sum x_0x_1 + b_{k-1}\sum x_0x_{k-1} = \sum x_0Y,$$

$$b_0\sum x_1x_0 + b_1\sum x_1^2 \ldots\ldots + b_{k-1}\, x_1x_{k-1} = \sum x_1Y \ldots\ldots$$

$$b_0\sum x_{k-1}x_0 + b_1\sum x_{k-1}x_1 \ldots\ldots + b_{k-1}\sum x_{k-1}^2 = \sum x_{k-1}Y \qquad (6)$$

(The summation index, i, is not shown in order to simplify notation)

The normal equations express the relationship between the variables x_0 through x_{k-1} based on observations numbered from i = 1 to i = n. The relationship could be determined exactly if the measurement process was noise-free. In the presence of measurement noise the metrologist must be content to consider the solution of-the normal equations from measurement data as approximations.

$$X'X\hat{B} = X'Y \qquad (7)$$

(where estimates of the coefficients are denoted by the hat (^))

The assumptions implicit in least squares fitting are that, a) the approximate relationship of variables is known, b) that where a series of observations Y are made they have a common variance and c) that all the random errors in the Y's are independent in the statistical sense. The method of least squares is unaffected by the system of coding used in setting up the model, provided that it is used consistently. The coding used can, however significantly affect the conditioning of the matrices and hence the ease of solution of the normal equations.

When the matrix X is of full rank, the normal equations can be solved for the set of maximum likelihood regression coefficients B by use of the inverse of X'X (sometimes called the covariance matrix).

$$\hat{B} = (X'X)^{-1}(X'Y) \qquad (8)$$

Finally, the estimate of the variance of a general linear model with (k + 1) parameters is estimated from n measurements by:

$$s = \frac{Y'Y - BX'Y}{n - (k + 1)} = SSE/df \qquad (9)$$

The estimated variance is the "Sums of Squares for Error" divided by "the number of degrees of freedom" available for estimating the variance. The test of hypothesis of any of the regression coefficients uses a familiar t-test with the statistic:

$$t = \frac{B_i - Bi}{s\sqrt{c_{ii}}} \qquad (10)$$

A confidence interval for the estimate of the i coefficient is calculated for n measurements and k coefficients from:

$$\pm\, t_{\alpha/2}\, s\sqrt{c_{ii}} \qquad (11)$$

SAMPLE MULTIPLE LINEAR REGRESSION PROGRAM

The sample program, written in BASIC uses the input/output codes appropriate to Atari (Shepardson) computer systems. The program uses the screen to lay out the coefficient matrix B and the data matrix Y for convenience. Since the screen is limited to 40 columns, the program limits the number of unknowns to 5. This limitation is not intrinsic to the computational algorithm and may be overcome by the use of simple input schemes.

Now let's discuss the logic of a typical microcomputer program. A sample listing in BASIC is included for illustration. We will refer to changes in this simple program to show how the general linear model can be modified for typical calibration requirements. Notation used in this discussion agrees with that in equations (8) and (9).

ENTRY/FUNCTION	JUMP TO	RANGE
RUN To run MLR (initializes dimension statements for various arrays)	-----	IO-158
200 Operator defines number of observations, number of variables, number of constraints, and variable names.	20000	200-450
480 Set up screen column headings with Variable names and "Data" for ease in visualizing the matrix of regression coefficients X and that of Data.	30000	480-525
539 Fill the screen with a representation of the B and Y matrices. Trap out garbage non-numerics.	5750	539-581

ENTRY/FUNCTION	JUMP TO	RANGE (Cont.)
582 Compute X'X matrix. Store it in S temporarily. S is a scratch pad.	10000	582-595
596 Store X'X in a permanent location. Call it XPRIMEDX. Print. Note: scratch pads S↑A↑B are used for ease of understanding program flow. Memory can be saved by judicious use of other storage locations.	-----	596-598
599 Compute X'Y. Store in Matrix XPRIMEDY.	10000	599-600
601 Load X'X into A. Store in B temporarily. Store X'X inverse permanently in XPRIMEDXINV.	-----	601-610
610 Print covariance matrix (X'X). Integer function may be eliminated.	-----	620-630
700 Compute X'XINV • X'Y. Store in matrix S (best fit coefficients).	-----	700-710
719 Compute pooled estimate of variance.	-----	719-790
795 Screen copied to printer.	32000	795-800
810 Print variance of regression coefficients (denominator of equation (10)).	-----	810-820
5740 Screen input format.	-----	5740-5750
10000 General subroutine to multiply matrices. If N = P second matrix is set to column. If N = 0 then the rank of second matrix is P - 1.	-----	10000-10040
11000 Inverts Matrix A. Stores result in Matrix B.	-----	11000-11500
20000 Stores names of variables as string in A$.	-----	20000-20030

ENTRY/FUNCTION	JUMP TO	RANGE (Cont.)
30000 Retrieves variable name from A$. Copies to screen as column headings.	-----	30000-30030
32000 Copies screen to printer.	-----	32000-32060

USE OF LINEAR MODELS IN ANEMOMETRY

It is usually helpful to go through an example. Data from the calibration of a velometer are provided in Figure 1. The instrument has two jets and an orifice, all of which require calibration between 200 and 1000 ft/min air velocity.

Since only one jet or orifice can be used on the instrument at a time, the linear coefficients of two of them are always set to zero. We choose to present "measured" air velocity as a function of velocity indicated by the velometer when it is used with each of the individual jets or orifices. The Figure 2 model, which assumes that the instrument is linear over its range, yields a poor fit to the calibration data.

The best simultaneous straight line fit for this data estimates the regression coefficients b_1, b_2, and b_3, to be: 1.16(#3920),1.05(#3930), and 1.07(#2420) respectively. However, the estimate of the standard deviation (pooled with 12 degrees of freedom) is 35 ft/min. This is considered greater than the customary unrepeatability of measurements at individual points.

A better fit is probably possible. The likely choices are models with either second or third order powers of meter indications for terms. We want to pool the calibration data once more so we devise another linear model which includes all three jet/orifices.

The Figure 3 experimental matrix for a simultaneous polynomial fit to the same data has six columns. One column is for each of the regression coefficients being estimated. All of the data is pooled, resulting in seven degrees of freedom being left over for estimation of the common process variance.

The computer program can be easily modified to accommodate the new linear model. The following additions will automatically compute powers of measured velocity and insert them in the experimental X matrix.

580 PRINT "FOR EACH VARIABLE SPECIFY THE NUMBER OF TERMS OF POWER SERIES":FOR K=0 TO P-1:PRINT "COL #";K+1;" NAME ";:INPUT T$:GOSUB 20000:PRINT "# TERMS?":INPUT X:T(K)=X-1:NEXT K . . . (where T(K) carries the order of the power series in the Kth variable.)

581 PRINT "I'M FILLING OUT THE POWER SERIES FOR YOU NOW.":FOR I=0 TO R-1: FOR I=0 TO R-1:X=0:FOR K=0 TO P-1:FOR J=X TO X+T(K):X(I,J)=S(I,K)→(J-X+1) NEXT J:X=X+T(K)+1:NEXT K . . . this fills in the appropriate squares, cubes, and higher powers of indicated velocities as stored in T(K). It is worthwhile pausing to note here that this is the point at which a whole new series of interpolating functions could be constructed by machine. For example, at this point we could introduce X(I,J) = COS(S(I,K)).

DIMENSION statements (lines 151-154) must accommodate six variables instead of five.

Subroutine 5750 is optional. It sets up the X matrix on screen for convenience.

RESULTS OF FITTING POLYNOMIALS SIMULTANEOUSLY

The linear model allows us to fit polynomials for all three jet/orifices from the same pool of calibration data. We feel confident that the repeatability at each instrument indication would approach that at all other indications if the process was repeated long enough. The standard deviation estimated from fifteen measurements after estimating coefficients to second order for three ranges is 16 ft/min. The estimate has nine degrees of freedom. We choose not to retain a fit to third order coefficients without more data since it gains us no significant reduction over this residual variance. The results are in Figure 4.

CONSTRUCTING A CALIBRATION CONFIDENCE INTERVAL

It is apparent from looking at the relative sizes of the second coefficients and their variance that the residual variance cannot be reduced significantly below 16 ft/min with the data available. We can proceed to calculate a confidence interval without fear that it will be affected by poorness of fit. The interval for orifice #3920 is:

$$y = x_1 \cdot (1.374 \pm t_{\alpha/2} \cdot 0.045) + x_1^2 \cdot (-2.62E-04 \pm t_{\alpha/2} \cdot 5.34E-05) \qquad (12)$$

APPLICATION OF CONSTRAINTS IN LEAST SQUARES ANALYSIS OF PAIR-DIFFERENCE DATA

We now consider the problem where one or more units are assigned standard values and the remaining units are to be evaluated by comparison with the standards and with themselves. Common examples of this application are found in standard cells, resistor banks, and mass sets. The values of the units can be found directly by application of constraints. Hughes et al(2) developed the approach to applying constraints to calibration data. A constraint is a linear combination of calibration variables with an assigned value.

$$\sum_k g_k \cdot b_k = L \qquad (13)$$

The method of applying constraints is best demonstrated with an example. We choose the NBS design for maintaining a bank of six standard cells described by Eike et al(3). The assigned value of the bank mean is the constraint.

The X matrix is augmented with a row and a column with all elements zero but the last one in the major diagonal. Next we augment the Y matrix with the constraint L. Finally, we augment the normal equations with the full constraint. Figure 6 illustrates the approach using data from NBS and the Bureau bank mean. (The calculations lead to the same results as those of reference (3).)

SOLVING THE NORMAL EQUATIONS UNDER THE METHOD OF CONSTRAINTS

Solution of the normal equations for least square error estimates of the standard cells must include the constraint for the bank mean. The constrained equivalent of equation (8) is:

$$B = \begin{vmatrix} X'X & g \\ g & 0 \end{vmatrix}^{-1} \begin{vmatrix} X'Y \\ L \end{vmatrix} \qquad (14)$$

This is illustrated by substitution of the Figure 5 information into equation (14).

COMPUTER PROGRAM CHANGES REQUIRED TO ACCOMMODATE CONSTRAINTS

The original program can be used to solve for the best fit values of any experimental design. However when a design is used repetitively it is most convenient to have the computer read the experimental design, X, from within the program. This saves effort and reduces the chance of human error. The following changes cause the previous experimental design to be read automatically.

```
540 FOR I=0 to R-l

542 FOR K=O TO P-1:GOSUB 30000: REM BEGIN THE LOOP
TO READ THE X & Y MATRICES.

550 READ X: X(I,K)=X: PRINT X(I,K); "ROW" ; NEXT K:
PRINT "DATA": INPUT X:X(I,Pt1)=X

552 TRAP 40000:PRINT CHR$(125):NEXT I:RESTORE
565:FOR K=O TO P:READ X:X(R,K)=X :NEXT K:RESTORE
565:FOR I=0 TO R:READ X:X(I,P)=X

553 FOR I=0 TO R:FOR K=O TO P:PRINT X(I,P):NEXT
K:?NEXT I:STOP:REM EXAMINE THE AUGMENTED X MATRIX.
YOU CAN REMOVE THIS AFTER YOU'RE SURE IT'S OK.

554 PRINT" SUM OF SIX CELLS ";:INPUT X:X(R,P+1)=X:
REM THIS IS THE CONSTRAINT. SEE LINE#566.

560-561 DATA (containing the un-augmented X matrix)

565 DATA 0,0,0,0,0,0,1 :REM BOTTOM LINE OF X MATRIX
(cONstRAint ON x)

566 DATA 1,1,1,1,1,1,0 :REM AUGMENTATED ROW/COLUMN
OF X'X MATRIX
```

SUMMARY

Calibration is a process of relating some property of properties of an instrument to a measured parameter. A useful model for this process is a sum of variables with constant (linear) coefficients. When we fit calibration data to such models by least square error criteria we have a tool of intuitive appeal with useful analytical properties. These properties allow us to estimate random uncertainties in the calibration process, subject to the underlying assumptions. The assumptions are that 1) we already know the general form of the relationship between variable(s) and observables, 2) all observations are statistically independent (uncorrelated), and 3) the observations are all characterized by the same expectation value for the variance. For confidence interval construction, we also added the assumption that the population of observations possessed a Gaussian distribution so that we can use its well known properties in estimating uncertainties.

The general linear statistical model allows the Metrologist to "practice" with several different measurement designs. Each design can be evaluated for its usefulness in estimating specific calibration parameters. The same computer program with small changes, can be adapted to simultaneous estimation of several calibration relationships. This increases the statistical power of the estimation process over the conventional approach of segregating data by instrument/standard. The model is equally useful far constrained and unconstrained measurement designs.

SUGGESTIONS FOR FURTHER THOUGHT

Calibration histories can take on a new significance. Histories presently kept on paper can be stored instead on disk. The accumulation of data provides a further analytical resource. The general linear model can be designed to automatically estimate drift, operator bias or other effects. The data can be coded to permit laboratory management to determine precisely when the standard shifted if all data taken on all similar standards are coded into a large general linear model. Such possibilities require mainframe computer capacities. We will reserve this for the next explorer of general linear statistical models.

REFERENCES

1. Draper, N. R., Smith, H., Applied Regression Analysis, John Wiley and Sons, Inc., New York, 1966

2. Hughes III, C. G., Musk, H. A., "A Least Squares Method for Pair Comparison Measurements," Metrologia 8, 109-113(1972) Springer-Veriag. 1972

3. Eike, W. G., Cameron, 3. M., "Designs for The Maintenance of The Volt Maintained by a Small Group of Saturated Standard Cells," NBS Technical Note 430, 1967

FIGURE 1

INDICATED VELOCITY (Ft/Min)	MEASURED VELOCITY (Ft/Min) Jet #3920	Jet #3930	Orifice #2420
200	250	240	210
400	500	440	555
600	735	670	640
800	950	860	870
1000	1100	1000	1040

Figure 1 - Velometer Calibration Data

FIGURE 2

X =

x_1 (#3920)	x_2 (#3930)	x_3 (#2420)
200	0	0
400	0	0
		0
600/800		0
	0	0
1000	0/200	0
		0
0	400/600	0
0	1000 800	0
		0
0	0	200
0		
0	0	400 600
0	0	800
0	0	1000

Y =

250
500
735
950
1100
240
440
670
860
1000
210
455
640
870
1040

Figure 2 - The X and Y Matrices Filled with Figure 2 Data

Linear model ($y = b_1x_1 + b_2x_2 + b_3x_3 + e$)

Figure 3

X =

x_1	x_1^2	x_2	x_2^2	x_3	x_3^2
200	200^2	0	0	0	0
400	400^2				
•		200	200^2	0	0
0	0	0	0	1000	10002

Figure 3 - The Experimental Matrix for a Simultaneous Second Order Polynomial Fit

Model $y = b_1x_1 + b_2x_1^2 + b_3x_2 + b_4x_2^2 + b_5x_3 + b_6x_3^2$

FIGURE 4

ORIFICE/ JET	1ST COEFF	$s\sqrt{c_{ii}}$	2ND COEFF	$s\sqrt{c_{ii}}$
#3920	1.37	0.045	-2.62E-04	5.34E-05
#3930	1.24	0.045	-2.31E-04	5.34E-05
#2420	1.15	0.045	-1.01E-04	5.34E-05

Figure 4 - Results of Pooling Data in
Figure 1 (nine degrees of freedom)

FIGURE 5

	#1	#2	#3	#4	#5	#6	AUG		uV
	1	-1	0	0	0	0	0		-5.4
	1	0	-1	0	0	0	0		13.7
	0	1	-1	0	0	0	0		18.8
	0	1	0	-1	0	0	0		
	0	0	1	-1	0	0	0		17.7 -1.3
	0	0	1	0	-1	0	0		
	0	0	0	1	-1	0	0		4.8 5.9
x =	0	0	0	1	0	-1	0	Y =	9.5
	0	0	0	0	1	-1	0		3.5
	-1	0	0	0	1	0	0		-22.7 -19.1
	-1	0	0	0	0				
	0	-1	0	0	0	11	0		-27.9
	1	0	0	-1	0	0	0		12.5
	0	1	0	0	-1	0	0		23.7
	0	0	1	0	0	-1	0		8.4
AUG	0	0	0	0	0	0	1		299.9 = L

(Augmented row/col)

Figure 5 - Comparison of Six Cells Constrained
By **Bank Mean. (Difference Data From Reference (3)) (Augmented by Constraint)**

FIGURE 6

	+5	-1	-1	-1	-1	-1	+1	-1	62.6
	-1	+5	-1	-1	-1	-1	+1		93.5
	-1	-1	+5	-1	-1	-1	+1		-20.6
B =	-1	-1	-1			-1			-13.5
	-1	-1	-1	+5-1	+5-1	-1	+1+1		-50.0
	-1	-1	-1	-1	-1	+5	+1		-72.0
	+1	+1	+1	+1	+1	+1	0		299.9

Figure 6 - **Solution of The Normal Equations (14) to Include the Constraint**

```
 10 REM GENERAL PURPOSE PROGRAM FOR MULTIPLE
 20 REM LINEAR REGRESSION ANALYSIS. USER
 30 REM SPECIFIES GENERAL LINEAR MODEL. SEE
 40 REM "APPLIED REGRESSION ANALYSIS" BY
 50 REM DRAPER&SMITH (WILEY SERIES IN PROBA-
 60 REM BILITY&MATHEMATICAL STATISTICS 1966)
 70 REM THIS PROGRAM IS WRITTEN IN ATARI DIALECT
 80 REM OF BASIC. ALL STRING ARRAYS ARE ONE
 90 REM DIMENSIONAL.  ARITHMETIC ARRAYS ARE
100 REM CONVENTIONAL.  PROGRAM PREPARED FOR
110 REM U.S. NAVY PRIMARY STANDARDS LAB BY
120 REM L.S. MORDECAI 10/81. PRESENTED
130 REM TO MEASUREMENT SCIENCES CONFERENCE
140 REM 1/83.
150 DIM A$(100),T$(6),L$(6):REM COLUMN HEADINGS
       ARE STORED AS 1 STRING IN A$.
151 DIM X(99,5):REM THE OBSERVATION MATRIX.
       COLUMNS 0 TO P-1 ARE X. COLUMN P
       IS USED TO STORE OBSERVATIONS, Y.
152 DIM XPRIMEDX(5,5),XPRIMEDY(5,1):REM X'X
       & X'Y MATRICES FOR 5 VARIABLES.
153 DIM XPRIMEDXINV(5,5):REM INVERSE X'X.
154 DIM A(5,5),B(5,5),S(5,5):REM SCRATCH PADS.
155 REM ALL DIMENSIONS SET FOR 5 VARIABLES
       AND 99 MEASUREMENTS. CHANGE AS NEEDED.
158 DIM XC$(39):REM THIS IS USED TO COPY
       SCREEN TO PRINTER. (PUT AND GET).
200 GRAPHICS 0:PRINT "INPUT THE NUMBER OF
       OBSERVATIONS ";
220 INPUT R:PRINT "HOW MANY CONSTRAINTS?":
       INPUT C:R=R+C:REM SET NUMBER OF ROWS
       IN X & Y MATRICES.
225 PRINT CHR$(125):PRINT "SPECIFY THE NUMBER
       OF VARIABLES":REM CHR$(125) IS CLEAR
       SCREEN.
227 PRINT "LIMIT IS SET TO 5 CHARACTERS
       AT PRESENT."
229 REM CHANGE DIMENSION STATEMENTS IF NEEDED.
240 INPUT P:IF P>5 THEN GOTO 245:REM SAFEGUARD
       GOING OVER DIMENSIONED MATRICES.
244 GOTO 250
245 PRINT "CHANGE DIMENSION STATEMENTS(PARTICU-
       LARLY LINES 150-154 OR REDUCE NUMBER
       OF UNKNOWNS IN YOUR MODEL."
246 GOTO 10
250 REM VARIABLE NAMES HEAD THE COLUMNS.
       LIMIT OF FIVE SET BY DIMENSIONS.
270 PRINT CHR$(125):PRINT "NAME COLUMNS
       1 THROUGH ";P
390 MAXLEN-6:REM SET SIZE OF COLUMN NAMES.
400 FOR K=0 TO P-1:PRINT "COLUMN# ";K+1;
       " NAME":INPUT T$:REM NAME OF Kth
       VARIABLE.
410 GOSUB 20000:NEXT K:REM COLUMN (VARIABLE)
       NAMES ARE GOING INTO 1 DIM STRING.
420 PRINT "CHECK COLUMN NAMES":FOR K=1 TO
       300:NEXT K:PRINT CHR$(125):REM PAUSE
       TO READ SCREEN. ARE NAMES OK?
430 FOR K=D TO P-1:GOSUB 30000:REM READ THE
       NAMES AS STORED IN A$.
440 PRINT K;" ";T$:NEXT K
450 PRINT "COLUMNS NAMED OK?  (Y OR NO)":
       INPUT T$:IF T$="N" THEN GOTO 270
480 REM INPUT EXPERIMENTAL MODEL (FILL THE X
       MATRIX.  THIS IS A GENERALIZED PROGRAM
       VERSION.
500 PRINT CHR$(125)
510 FOR K=0 TO P-1
520 GOSUB 30000:POSITION 6*K,1:PRINT T$:NEXT K
525 POSITION 6*K,1:PRINT " DATA"
539 J=0
540 FOR I=D TO R-1:J=J+1:IF J=21 THEN GOSUB
       5750:REM LARGE MODELS WILL FILL SCREEN.
       THIS CLEARS ALL BUT HEADINGS.
547 FOR K=0 TO P:TRAP 40000: REM THIS IS A
       DOUBLE LOOP TO FILL THE TWO DIMENSIONAL
       X MATRIX WITH NUMERICS(NUMBERS).
543 REM THE OBSERVATIONS GO IN THE Pth COLUMN
       FOR UNCONSTRAINED MODELS, & IN THE
       P+1th COLUMN FOR CONSTRAINED ONES.
550 TRAP 550:POSITION 6*K,J+2:INPUTX:X(I,K)=X
570 NEXT K:NEXT I:REM YOU HAVE FILLED THE
       EXPERIMENTAL AND OBSERVATIONAL MATRICES.
580 TRAP 40000:RESET THE TRAP. DISPLAY ERROR
       DIAGNOSTICS OF COMPUTER.
582 PRINT CHR$(125):PRINT "COMPUTING X'X
       MATRIX":REM I LIKE TO KNOW WHAT'S
       HAPPENING INSIDE THE MACHINE.
583 N=0:GOSUB 10000:REM MULTIPLY X(TRANSPOSE)
       AND X MATRICES TOGETHER. THIS IS
       SOMETIMES NOT A LIBRARY ROUTINE.
584 REM FOR I-0 TO P-1                     S
585 REM |  FOR J=N TO P-1                  U
586 REM |  |  FOR K=0 TO R-1               B
587 REM |  |                               R
588 REM |  |  S=S+X(K,I)*X(K,J)
589 REM |  |                               i
590 REM |  |  NEXT K:S(I,J)=S              0
591 REM |  |                               0
592 REM |  NEXT J                          0
593 REM |                                  0
594 REM -NEXT I                            *
595 REM THIS IS HOW SUBR 10000 WORKS       *
596 REM * ********************************
597 FOR I=0 TO P-1:FOR J=0 TO P-1:XPRIMEDX(I,J)=
       S(I,J):NEXT J:NEXT I
598 PRINT "X'X MATRIX":FOR I=0 TO P-1: FOR
       J=0 TO P-1:POSITION J*7,I+5:PRINT
       XPRIMEDX(I,J):NEXT J:NEXT I
599 PRINT "NOW CALCULATING X'Y":N=P:GOSUB
       10000:FOR I=0 TO P-1:XPRIMEDY(I,1)
       =S(I,P):PRINT XPRIMEDY(I,1):NEXT I
600 FOR I=1 TO 200:NEXT I:REM PAUSE & READ.
601 REM ********************************
602 REM INVERT X'X. FIRST LOAD IT INTO A.
       THEN INVERT A IN LINES 11000 TO
       12000 (B IS A INVERTED). PUT B IN
603 REM MATRIX XPRIMEDXINV PERMANENTLY.
       (THIS IS RATHER WASTEFUL OF RAM. IT
       IS A CLEAR ALGORITHM, HOWEVER.)
607 REN *********************************
610 FOR J=0 TO P-1: FOR I=0 TO P-1:A(J,I)=
       XPRIMEDX(J,I):B(J,I)=0:NEXT I: B(J,J)
       =1:NEXT J
619 OPEN#3,4,0,"S:":REM OPEN IOCB TO SCREEN.
620 PRINT CHR$(125):PRINT"XPRIMEDXINV":GOSUB
       11000:FOR I=0 TO P-1:FOR J=0 TO
       P-1:XPRIMEDXINV(I,J)=B(I,J)
630 POSITION 7*J+1,I+3:PRINT INT(XPRIMEDXINV(I,J)
       *1000+0.5)/1000:NEXT J:NEXT I:REM
       ROUNDS OFF TO 3 PLACES. IT WILL
631 REM ROUND SMALL VALUES DOWN TO ZERO.
       SINCE ARITHMETIC ACCURACY OF ALGORITHM
       IS NOT AFFECTED, MODIFICATION IS
632 REM OPTIONAL.  IT IS USEFUL TO SEE X'X
       INVERSE ONLY DURING EXPERIMENT DESIGN.
700 REM *** COMPUTE XPRIMEDXINV*XPRIMEDY***
701 REM THE RESULTANT IS THE MATRIX OF THE
702 REM REGRESSION COEFFICIENTS. STORE THESE
       IN THE MATRIX S.
```

```
709 PRINT "THE REGRESSION COEFFICIENTS ARE"
710 FOR I=0 TO P-1:S=0:FOR J=0 TO P-1:S=S+
        XPRIMEDXINV(I,J)*XPRIMEDY(I,J)*
        XPRIMEDY(J,1):S(I,1)=S:NEXT J
711 PRINT S(I,1):NEXT I:REM (COEFFICIENTS)
719 REM NEXT COMPUTE THE ESTIMATED VARIANCE.
720 BXPRIMEDY=0:FOR I=0 TO P-1:BXPRIMEDY=
        BXPRIMEDY+S(I,1)*XPRIMEDY(I,1):NEXT I
730 YY=0:FOR I=0 TO R-1:YY=YY+X(I,P)→2:NEXT I
740 SSE=YY-BXPRIMEDY:VARIANCE=SSE/(R-P):REM
        VARIANCE=SUMS OF SOUARES FOR ERROR
        DIVIDED BY DEGREES‘OF FREEDOM.
750 PRINT "POOLED VARIANCE"
75I PRINT "FROM (BEST FIT MINUS OBSERVED)
        SQUARED"
760 PRINT "DIVIDED BY NUMBER OF DEGREES OF
        FREEDOM AFTER ESTIMATING COEFF."
780 PRINT:PRINT "VARIANCE= ";VARIANCE
784 PRINT "STANDARD DEVIATION = ";SQR(VARIANCE)
790 PRINT "WITH ";R-P;" DEGREES OF FREEDOM."
795 GOSUB 32000:REM COPY SCREEN TO PRINTER.
        YOU MAY ELECT TO LPRINT IT.
800 OPEN #3,4,0,"S:":REM NEXT SCREENFUL COMING.
810 PRINT "VARIANCE OF EACH REGRESSION COEF-
        FICIENT IS"
820 FOR I=0 TO P-1:PRINT "COEFF.# ";I+1;" ";
        VARIANCE*XPRIMEDXINV(I,1):NEXT I
830 GOSUB 32000:CLOSE #3
840 END:REM --------------------------------
5740 REM THIS SUBROUTINE CLEARS MATRIX AT
        ROW NUMBER 21 ON THE SCREEN, AND
        LEAVES THE COLUMN HEADINGS.
5750 FOR A=2 TO 21:FOR B=0 TO 38:POSITION
        B,A+1:PRINT " ":NEXT B:NEXT A:J=2:RETURN
9999 REM ************************************
10000 REM SUBROUTINE TO MULTIPLY X' AND X
        AS WELL AS X' AND Y. SET N = 0 OR P
        RESPECTIVELY FOR X'X & X'Y.
10030 FOR I=0 TO P-1:FOR J=N TO P-1+N/P:
        S=0:FOR K=0 TO R-1:S=S+X(K,I)*X(K,J):
        NEXT K:S(I,J)=S:NEXT J:NEXT I
10040 PRINT "FINISHED":RETURN
10999 REM ************************************
11000 REM SUBROUTINE TO INVERT A. EXITS
        WITH THE INVERSE OF A IN 8. THIS
        SUBSTITUTES FOR "MATINV" COMMAND.
11150 FOR J=0 TO P-l
11160 FOR I=J TO P-1
11170 IF A(J,I)<>0 THEN GOTO 11210
11180 NEXT I
11190 PRINT "THE EXPERIMENTAL MATRIX WAS
        SINGULAR. THE VARIABLES ARE UNDER-
        DETERMINED."
11200 END
11210 FOR K=0 TO P-l
11220 S=A(J,K)
11230 A(J,K)=A(I,K)
11240 A(I,K)=S
11250 S=B(J,K)
11260 B(J,K)=B(I,K)
11270 B(I,K)=S
11280 NEXT K
11290 T=1/A(J,J)
11300 FOR K=0 TO P-l
11310 A(J,K)=T*A(J,K)
11320 B(J,K)=T*B(J,K)
11330 NEXT K
11340 FOR L=0 TO P-l
11350 IF L=J THEN GOTO 11410
11360 T=-A(L,J)
11370 FOR K=0 to P-l
11380 A(L,K)=A(L,K)+10*T*A(J,K)/10:REM THESE
        NUMBERS ARE SMALL. ROUND OFF ERROR
        MAY BE A PROBLEM. RECOMMEND YOU
        CALCULATE WHAT IT IS FOR YOUR EXPERIMENT
11390 B(L,K)=B(L,K)+10*T*B(J,K)/10
11400 NEXT K
11410 NEXT L
11420 NEXT J
11500 RETURN
19998 REM ************************************
19999 REM SUBROUTINE TO READ VARIABLE NAMES
        INTO A$. COMPANION SUBROUTINE AT
        LINE #30000 COPIES THEM BACK OUT.
20000 L=LEN(T$):IF L>MAXLEN THEN L=MAXLEN
20010 L(K)=L:START=K*MAXLEN+1:REM WE ARE
        STORING ALL VAR. TITLES IN ONE LONG
        STRING. A 2 DIM. STRING IS PREFERABLE.
20020 A$(START,START+L)=T$
20030 RETURN
30000 START=K*MAXLEN+1
30010 T$=A$(START,START+L(K)-1:REM LENGTH
        OF COLUMN NAME IS IN T(K).
30030 RETURN
32000 REM PRINT SCREEN TO PRINTER
32020 XC$="
          ":REM 39 SPACES
32030 FOR YLOOP=O TO 23:POSITION 1,YLOOP:FOR
        XLOOP=1 TO 39:GET #3,XC:XC$(XLOOP,XLOOP)
        =CHR$(XC):NEXT XLOOP
32040 LPRINT XC$
32050 NEXT YLOOP
32060 CLOSE #3:RETURN
32070 REM SCREEN TO PRINTER ROUTINE FROM
        COMPUTE! MAY'81 PAGE 78 BY LINDSAY.
        PUBL. SMALL SYSTEMS SERVICES
32071 REM P.O.BOX 5406 GREENSBORO, N.C. 27403
32080 REM SUBROUTINE TO INVERT A MATRIX
        FROM "SOME COMMON BASIC PROGRAMS"
        BY POOL&BORCHERS. PUBLISHED BY OSBOURNE
        & ASSOCIATES 1978
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MEASUREMENT SCIENCE CONFERENCE

HYATT RICKEYS, Palo Alto, California
January 20 and **21, 1983**

Please Address Reply To:

DOOR PRIZE PROGRAM RESULTS

4:30 p.m., Friday, January 21, 1983

The quality and quantity of prizes donated for this year's Door Prize Program were outstanding -- 41 contributors and 63 prizes having a total value in excess of $9,100.00. Included were analog and digital hand-held and bench-top electrical, electronic and mechanical measuring instruments, calculators, texbooks, cash and other goodies ranging in individual prize value from $5.00 to $1,085.00. A one-week's use of a 1983 Lincoln Automobile, Prize No. (1), a cryogenic thermometer (Prize No. (21), a combination gaussmeter/fluxmeter (Prize No. 29) and a hands-on microprocessor course (Prize No. 54) were among some of the unique prizes offered. Also, and on the assumption that the attendees would appreciate winning vintage or recently new (but mint condition and fully operational) equipment, we openly solicited donations in this area. Examples are Prize No.'s (12), (13) and (14): the taut-band DC voltmeter, DC ammeter and the pulse generator. In addition to the above, a free registration to the 1984 MSC (in Southern California) was awarded to one of the 1983 MSC attendees.

A complete listing of all prizes, donators, and lucky winners is given on the following pages. A copy of the instructions given to attendees at the start of the Conference is also included.

Special Recognition and our Sincere Thanks is hereby extended to the many organizations and individuals who donated the prizes to this year's Conference. It was these organizations and individuals, through their gracious contributions, that made this year's Door Prize Program such a fantastic success.

For the Conference Committee,

Bob

Bob Couture
Door Prize Chairman
Measurement Science Conference, Inc.

1983 MSC

DOOR PRIZE CONTRIBUTORS

Our very special thanks go to the organizations and individuals listed below. Without their gracious contributions the 1983 MSC Door Prize Program would not have been possible.

- Aeronutronic-Ford
- Ballantine Laboratories, Inc.
- Basic Systems Corporation
- Beckman Instruments, Inc.
- Bruel & Kjaer Instruments
- Cutlass Electronics
- Dale-Dahl Associates
- Dalfi, Inc.
- Datron Instruments, Inc.
- Data Precision Corporation
- DynaSales Company
- Electro Rent Corporation
- Electro Scientific Industries, Inc.
- Flow Technology, Inc.
- John Fluke Manufacturing Co.
- Guildline Instruments, Inc.
- Honeywell, Inc.
- Robert Irvine
- Lakeshore Cryotronics, Inc.
- Measurement Science Conference
- Metron Corporation
- PCB Piezotronics, Inc.
- Probe Master
- Quality Magazine
- Racal-Dana Instruments, Inc.
- RFL Laboratories, Inc.
- Rockwell International, Inc.
- Ruska Instruments, Inc.
- Simco Electronics
- Standard Reference Labs.
- K. Y. Rogers, Inc.
- L. S. Starrett Company
- Spectracom Corporation
- Tektronix, Inc.
- True Time Instruments
- U.S. Instrument Rentals
- Valhalla Scientific, Inc.
- Viking Laboratories
- Ward/Davis Associates
- Wahl Instrument Company
- Weinchel Engineering Company

MEASUREMENT SCIENCE CONFERENCE
DOOR PRIZE PROGRAM RESULTS

January 21, 1983

PRIZE NO.	DONATOR	PRIZE	WINNERS
(1)	AERONUTRONIC DIVISION of FORD AEROSPACE and COMMUNICATIONS CORP. FORD MOTOR COMPANY Ford Road, P. O. Box A Newport Beach, CA 92663 Arranged by: John Schulz (714) 759-5487	• One-week use of 1983 Lincoln Automobile Winner will arrange with FORD Motor Co. (John Schulz) for a mutually agreeable delivery date and pick-up in Long Beach, CA. The automobile will come with a full tank of gasoline and be fully insured. Additional gasoline must be purchased by winner.. Upon completion of the one-week (7-day) use period, the automobile must be returned to the same Long Beach location. This prize must be redeemed within the 1983 model year. Approx retail value: $450.00	Harry B. Haymes, Supervisor Sanders Associates, Inc. Nashua, NH
(2)	BALLANTINE LABORATORIES, INC. P.O. Box 97 Boonton, NJ 07005 Arranged by: M. Lichtenstein (201) 335-0900	• Ballantine Laboratories Model 3028A, Option 20, 3 1/2 digit bench-top (portable) DMM Has both digital and analog display, high/low resistance ranges, diode check and many other features. Approx retail value: $365.00	Max Frank Streeter, USN Electronics Technician Puget Sound Naval Shipyard Bremerton, WA
(3)	BASIC SYSTEMS CORPORATION 2359 De La Cruz Blvd. Santa Clara, CA 95050 Arranged by: Larry Hodel (408) 727-1800	• Thermo-Electric Model 31171000 Hand-Held Digital Temperature Meter with penetration thermocouple probe. Approx retail value: $274.00	Robert Biller, Marketing Manager Micro-Tel Bart, MD

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(4)	BECKMAN INSTRUMENTS, INC. 210 Ranger Brea, CA 92621 Arranged by: Dennis White (714) 993-8855	• Beckman Instruments Model HD110 Heavy Duty Hand-Held DMM Resistant to accidental drooping, contamination and overloads, bright NATO yellow color. Approx retail value: $189.00	Ken W. Wibbenmeyer, Unit Chief McDonnell Douglas St. Louis, MO
	BRUEL & KJAER INSTRUMENTS, INC., 1542 E. Katella Anaheim, CA 92805 Arranged by: Rob Greene (714) 978-8066	• Two Complete Sets of Six-each Hardcover Handbooks (See below for description and prize number.)	
(5)		• Set of Six Hardcover Handbooks Acoustic Noise Measurements Architectural Acoustics Frequency Analysis Mechanical Vibration and Shock Measurements Noise Control Strain Measurements Approx retail value: $43.00	Patsy May Dea, Sr. Statistician TRW Redondo Beach, CA
(6)		• Set of Six Handcover Handbooks Acoustic Noise Measurements Architectural Acoustics Frequency Analysis Mechanical Vibration and Shock Measurements Noise Control Strain Measurements Approx retail value: $43.00	Duncan F. McDonell, Mech. Engineer Pacific Missile Test Center Pt. Mugu, CA

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(7)	CUTLASS ELECTRONICS P.O. Box 6503 18039 Crenshaw Blvd. Torrance. CA 90504 Arranged by: Dean Marxer (213) 324-7360 (714) 549-9358	• Valhalla Scientific Model 3302 Hand-Herd DMM Approx retail value: $129.00	Edgar Lee Graef, Elect. Technician Navy Primary Standard's Lab Washington, DC
(8)	DALE DAHL ASSOCIATES 2738 West Main Street Alhambra, CA 91801 Arranged by: Gene Bleasdale (213) 682-3417	• Samsonite Carry-On Luggage Approx retail value: $95.00	Charles E. Weber, Eng. Supervisor Grumman Aerospace Corp. Bethpage, NY
(9)	OALFI, INC. 100 Carroll Canyon Road San Diego, CA 92131 Arranged by: C. Van Winkle (714) 578-9500	• Imported Beer Stein Especially manufactured in Germany for DALFI, Inc. Approx retail value: $65.00	Gary L. Smith, Training Manager Metron Corp. Rancho Cucamonga, CA
(10)	DATA PRECISION DIV. OF ANALOGIC CORPORATION Danvers, MA 01923 Arranged by: M. Koulopoulos, Jay Long and John Seney (617) 246-1600	• Data Precision/Analogic Model 938 Hand-Held Digital Capacitance Meter Approx retai'1 value: $219.00	Alfred B. Wingfield, Leader Marine Corp Logistics Base Barstow, CA
(11)	DATRON INSTRUMENT, INC. 3401 S.W. 42nd Avenue Stuart, FL 33494 Arranged by: Geoffrey Cannell (305) 283-0935; and David Walker, (714) 545-8115	• $50.00 Cash	Algie L. Lance, Sr. Scientist TRW Redondo Beach, CA

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
	DYNASALES COMPANY P. 0. Box 6757 Los Angeles. CA 90022 Arranged by: Bob Marshall (213) 268-1175	● Two Vintage Westinghouse Taut-Band dc Meters (Sixteen-years old, but new and unused. See below for description and prize number.)	
(12)		● Westinghouse Model PX161, Style 291B745A26 Taut-Band DC Voltmeter. Has 3, 7.5, 15, 30, 75, 150, 300 & 750 volt ranges, 11" mirrored scale and 1/2 of one percent accuracy. *1972 price Approx retail value: $286.00	Ernie B. Crisologo, Tech. Manager Viking Laboratories, Inc. Mt. View, CA
(13)		● Westinghouse Model PX161, Style 291B744A27 Taut-Band DC Ammeter. Has 11" mirrored scale and 1/2 of one percent accuracy (for use with 50 mV shunt). *1972 price Approx retail value: $286.00	Harvey M. Zall, Site Manager Simco/NASA Santa Clara, CA
(14)	ELECTRO RENT CORP. 4131 Vanowen Place Burbank, CA 91505 Arranged by: Howard Blackman (213) 843-3131	a Interstate Electronics Corp. Model P24 Pulse Generator Instrument was purchased in 1977 for use as a rental unit. It has been used but is in very good condition, fully operational and is complete with original operator's manual. Features include: 1 Hz to 50 MHz pulse and squarewave, 10 ns to 1 s width and delay, single output + or - pulse with DC	Ronald Broschinsky, QE Metrology Brunswick Corp Costa Mesa, CA

PRIZE NO.	DONATOR	PRIZE	WINNERS
	ELECTRO RENT CORP. (continued)	offset, variable rise and fall from 5 ns to 0.5 s, 10 V pulses into 50 ohms, exclusive constant duty cycle and many more features. Approx retail value: $995.00 (1977)	
	ELECTRO SCIENTIFIC INDUSTRIES, INC. 14000 N.W. Science Park Portland, OR 97279 Arranged by: Jim Currier and Doug Strain (503) 641-4141	• Two each Electro Scientific Industries Model SR-1 Standard Resistors (See below for prize number.)	
(15)		• ESI, Inc. Model SR-1 Standard Resistor I-K ohm Approx retail value: $155.00	Ervin V. Abbott, Engr. Specialist Vought Corporation Dallas, TX
(16)		• ESI, Inc. Model SR-1 Standard Resistor 10-K ohm Approx retail value: $155.00	Dave Hopping, Cal Lab Supervisor Hewlett-Packard Santa Rosa, CA
(17)	FLOW TECHNOLOGY, INC. 2363 Boulevard Circle, Suite 1 Walnut Creek, CA 94595 Arranged by: Gene Bleasdale of Dale-Dahl Associates, Co. Representative (415) 933-9595	• Leather Briefcase Approx retail value: $95.00	Ken Carrington, Section Manager csc Arnold, AFS, TN

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(18)	JOHN FLUKE MANUFACTURING CO. 2300 Walsh Avenue Santa Clara, CA 95050 Arranged by : Joe Murdica and Hines Falkenberg (408) 727-0513	• John Fluke Co.Model 8060A DMM Approx retail value: $349.00	Christine G. Meek, Salesperson Crystal Engineering Motto Bay, CA
(19)	GUILDLINE INSTRUMENT CD. 2 Westchester Plaza Elmsford, NY 10523 Arranged by: Ed Nemeroff and Bob Gangawer (914) 592-9101	• Kodak Model 6000 Disc Camera Approx retail value: $70.00	Tad Mukaihata, Manager, Met Lab Hughes Aircraft Culver City, CA
(20)	PROFESSOR ROBERT IRVINE of Cal Poly - Pomona (a personal donation by the author)	• A reference text book on "Operational Amplifiers" Published in 1981 by Prentice - Hall Book covers the construction and characteristics of the various types of Op Amps, and their use as a circuit element in digital, non-linear and active filter circuits. Approx retail value: $25.00	Kenneth M. Walczak, Scientist Owens-Corning Fiberglas Granville, OH
(21)	LAKESHORE CRYOTRONICS, INC. 64 E. Walnut Street Westerville, OH 43081 Arranged by: Warren Pierce (614) 891-2243	• Lakeshore Cryotronics Model DI-8 DIGI-K Cryogenic Thermometer with thumb-wheel set-point alarms - operates -in range of 4 to 330 K with resolution of 1 K. Accuracy is +(1% or 1 K) whichever is greater. Approx retail value: $795.00	John Milburn, Lead Instrumentation Watkins Johnson San Jose, CA

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(22)	MEASUREMENT SCIENCE CONFERENCE, INC.	• Free Registration to 1984 Measurement Science Conference Approx retail value: $135.00	Guy Fleming, Electronic Supervisor United Technology Sunnyvale, CA
(23)	METRON CORPORATION 9681 Business Center Drive Rancho Cucamonga, CA 91730 Arranged by: Art Plourde and Bill King (714) 980-6166	• Complete Set of (16) Textbooks for Metron Institute of Measurement Technology (MIMT Course in Physical and Electronic Metrology in SI Units Approx retail value: $200.00	Philip E. Benoit, Mech. Engineer USN Metrology Engineering Center Pomona, CA
(24)	PCB-PIEZOTRONICS 3425 Walden Avenue Dupew, NY 14043 Arranged by: Roy Maimes PCB (716) 684-001, and Fred Dahl of Dale-Dahl Associates (213) 682-3417	. Craig Model LC-640 Pocket Calculator Approx retail value: $12.95	H. A. Taff, Chief Central Labs TVA Chattenooga, TN
	PROBE MASTER 4898 Ronson Court San Diego, CA 92111 Arranged by: Jimm Hoffmann (619) 560-9676	• Two Probe Master Products: An oscilloscope probe--and an attenuator. (See below for description and prize numbers.)	
(75)		. Probe Master Model PM2902RAE Miniature, 250-MHz Band-Width, X1 & X10 Oscilloscope Probe. Includes enoineerina accessory kit and readout actuator option which switches readout on all TEK scopes in X10 modes. Approx retail value: $79.95	Albert Hedrich, NBS Mechanical Products Washington, DC

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(26)	PROBE MASTER (continued)	Probe Master Model PM1058 40-dB, 2-Watt, 12-4 GHz Attenuator with type N connector. (Replaces TEK part #0110087-00) Approx retail value: $75.00	Jack H. Huey Lockheed Missile & Space Co. Sunnyvale, CA
(27)	QUALITY MAGAZINE Hitchcock Publishing Co. Hitchcock Building Wheaton, IL 60187 Arranged by: D. Templeton (312) 665-1000, and Dennis Seger (714) 891-2633	$25.00 Cash	John L. Minck, ADSP Manager Hewlett-Packard Palo Alto, CA
(28)	RACAL-DANA INSTRUMENTS, INC. #4 Goodyear Street Irvine, CA 92714 Arranged by: Norbert Langrich and Skip Schreiber (714) 859-8999	Racal-Dana Instruments Model 2000 A Danameter Hand-Held DMM Approx retail value: $400.00	Gerald Mason, Sr. Inst. Specialist Chemical Systems Division, UTC San Jose, CA
(29)	RFL INDUSTRIES, INC. Boonton, NJ 07005 Arranged by: Brad Bradbury (201) 334-3100	RFL Laboratories, Inc. Model 906,49935 and 906039 Combination Gaussmeter/Fluxmeter with Search and Hall Probes and Rechargeable Battery Pack (Hall-Probe Thickness = 0.039") Approx retail value: $1,085.00	Eugene A. Gleason, President Micro Surface Engineering, Inc. Los Angeles, CA
(30)	ROCKWELL INTERNATIONAL, INC. Defense Electronic Operations, 3370 Miraloma Ave. Anaheim, CA 92803 Arranged by: Diane Anderson (714) 632-4192	Rockwell International Model 4420 Orbiting Finishing Sander, Double Insulated, Ball Bearings, High Speed - 12,000 Orbits/Minute (w/sand paper) Approx retail value: $40.00	Richard A. Schultz, Physicist NWS, Seal Beach Pomona. CA

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(31)	RUSKA INSTRUMENT CORP. 3601 Dunvale Street Houston, TX 77081 Arranged by: Elliot Moser (713) 729-1447, and Gene Bleasdale of Dale-Dahl Associates (415) 933-9595	• Airways Executive Briefcase Approx retail value: $100.00	Herman Killmeyer, Engr. Supervisor USAF/AGMC/Newark AFS Newark. OH
	SIMCO ELECTRONICS 382 Martin Ave. Santa Clara, CA 95050 Arranged by: Carl Quinn (408) 727-3611	• Four Each Scherr Tumico Precision Dial Dynamometers Lever Action, 2 1/2" dial, Plus-Minus 50 to 250 grams force (See below for prize number.)	
(32)		• Scherr-Tumico Precision Dial Dynamometer (as described above) Approx retail value: $85.00	William Ivey, Section Head, Met. TRW Redondo Beach, CA
(33)		• Scherr-Tumico Precision Dial Dynamometer (as described above) Approx retail value: $85.00	Amber Christopher, Marketing US Instrument Rentals San Mateo, CA
(34)		• Scherr-Tumico Precision Dial Dynamometer (as described above) Approx retail value: $85.00	Martin D. Conway, Sales Manger Volumetrics Paso Robles, CA
(35)		• Scherr-Tumico Precision Dial Dynamometer (as described above) Approx retail value: $85.00	Stephen N. Cortis, Metrology US Army Warrier, MI

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(36)	STANDARD REFERENCE LABS, IMC. Coan Place/P.O. Box 388 Metuchen, NJ 08840 Arranged by: Dennis Koep (201) 549-9292	. Kodak Model 6000 Disc Camera Apnrox retail value: $70.00	David Rosenthal, Project Manager Newport Corp. Fountain Valley, CA
(37)	L. S. STARRETT COMPANY 6920 Hermosa Circle Buena Park, CA 90620 Arranged by: Gordon Hoehn (714) 739-0323	• L. S. Starrett Co. Model T230XRL 1" Outside Micrometer Caliper. Features include: Tungsten-carbide meas-suring faces, satin-chrome finish, ratchet stop, locknut and Cat. No. 910 case. (Measures to 0.0001 inch) Approx retail value: $55.00	Steven Greenwood, General Manager Crystal Engineering Baywood Park, CA
	SPECTRACOM CORPORATION 320 N. Washington Street Rochester, NY 14625 Arranged by: B. Hesselberth (716) 381-4827	• Two Quartz Travel Alarms (See below for prize number.)	
(38)		• Quartz Travel Alarm Approx retail value: $20.00	H.D. Farnsworth, Telecom Sls Spec. EIP Microwave, Inc. San Jose, CA
(39)		• Quartz Travel Alarm Approx retail value: $20.00	Paul R. Lange, Commander, AGMC USAF Newark, OH
	TEKTRONIX, INC. 3003 Bunker Hill Lane Santa Clara, CA 95050 Arranged by: Marvin Bail and Brian Shumaker	• Two ea. Tektronix, Inc. Oscilloscope Probes (See below for description and prize number)	

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(40)	TEKTRONIX, INC. (continued)	• Tektronix, Inc. Model P6106 250-MHz, X10 Oscilloscope Probe with readout. Designed for TEK 7000-series scopes but useable with other models. Approx retail value: 9131.00	Richard C. Wagner, Met. Engineer McDonnell Douglas Huntington Beach, CA
(41)		• Tektronix, Inc. Model P6106 250-MHz, X10 Oscilloscope Probe with readout. Designed for TEK 7000-series scopes but useable with other models. Approx retail value: $131.00	Clifford D. Koop, Manager Rockwell-Collins Cedar Rapids, IA
	TRUE TIME INSTRUMENT CO. 3243 Santa Rosa Ave. Santa Rosa, CA 95401 Arranged by: J. Van Groos and Victor Kunkel (707) 528-1230	• Three Prizes. (See below for description and prize numbers.)	
(42)		• Time Cube Approx retail value: $40.00	Philip Alderton, Marketing Manager Instrulab, Inc. Dayton, OH
(43)		• LCD Pen Watch Approx retail value: $10.00	Ron S. Kamerlink, President Novus Technology Los Altos, CA
(44)		• LCD Pen Watch Approx retail value: $10.00	Ron A. Ramirez, VP Marketing Weinschel Engineering Gaithersburg, MD

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(45)	U.S. INSTRUMENT RENTALS 2988 Campus Drive San Mateo, CA 94403 Arranged by: John Lee (714) 578-8280	• Leather Briefcase Approx retail value: $100.00	Clifford Duncan, Sr. Inst. Engr. Lockheed Missile & Space Co. Bremerton, WA
(46)	VALHALLA SCIENTIFIC 7576 Trade Street San Diego, CA 92121 Arranged by: Kevin Clark (619) 578-8280	• Valhalla Scientific Model 3301 Hand Held DMM Approx retail value: $90.00	Donald A. McSparron, Physicist NBS Washington, DC
	WAHL INSTRUMENT CO. 5750 Hannum Ave. Culver City, CA 90230 Arranged by: Chuck Blackburn (213) 641-6931	• Seven (7) Wahl Instrument Co. Products (See below for description and prize numbers.)	
(47)		• Wahl Inst. Co. Model 731-12 24-Hour Temperature Chart Recorder (0 to 100°F) Approx retail value: $185.00	Steven Dwyer, Reliability Analyst USN Metrology Engineering Center Pomona, CA
(48)		• Wahl Instrument Co. EGGRIGHT Egg Timer Approx retail value: $7.00	Kenneth J. Lund, Metrologist Rockwell International Anaheim, CA
(49)		. Wahl Instrument Co. EGGRIGHT Egg Timer Approx retail value: $7.00	Lionel Mordecai, Engr. Supervisor Navy Primary Standards Lab San Diego, CA
(50)		• Wahl Instrument Co. EGGRIGHT Egg Timer Approx retail value: $7.00	William A. Simmons, Manager Barrios Technology, Inc. Houston, TX

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(51)	WAHL INSTRUMENT CO. (continued)	• Wahl Instrument Co. EGGRIGHT Egg Timer Approx retail value: $7.00	J. Matt Chlupsa, Sr. Engineer RFL Boonton, NJ
(52)		• Wahl Instrument Co. EGGRIGHT Egg Timer Approx retail value: $7.00	Jan Smith, Manager Simco Electronics Santa Clara, CA
(53)		• Wahl Instrument Co. EGGRIGHT Egg Timer Approx retail value: $7.00	NOT AWARDED Disappeared during 1st day of Conference
(54)	WARD/DAVIS ASSOCIATES 3329 Kifer Road Santa Clara, CA 95051 Arranged by: Leon Hamner (408) 245-3700	• All-day Tutorial/Hands-On course on microprocessor in-circuit emulation as used in development of microprocessor hardware and software course utilizes Gould-Millennium products at Ward-Davis' Santa Clara Office and will be given at selected dates during 1983. Contact Mr. Hamner for specifics. Approx retail value: $400.00	Gary M. Nickus, Vice President FLW Hayward, CA
(55)	WEINSCHEL ENGINEERING CO. 29169 Heathercliff, No. 213 Malabu, CA 90265 Arranged by: Gary McNamarra (213) 457-4563	• $25.00 Cash	Roger D. Kottman, Engr. Technician Abbott Labs North Chicago, IL

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
	VIKING LABORATORIES • 5555-l Magnetron Blvd. San Diego, CA 92111 • 440 Bernard Ave. Mountain View, CA Arranged by: Ann Foran (Mountain View) (415) 969-5500, and Angela Ginn (San Diego) (619) 571-0337	• Two Gift Certificates for Viking Laboratory Calibration Services (See below for description and prize number.)	
(56)		• $50.00 Gift Certificate To be applied towards calibration'bf any one instrument. Calibration service may be obtained from either Viking Laboratory facility (San Diego or Mountain View, California).	Ashley Harkness, Lab Specialist Electro Test San Ramon, CA
(57)		. $50.00 Gift Certificate To be applied towards calibration'of any one instrument. Calibration service may be obtained from either Viking Laboratory facility (San Diego or Mountain View, California).	Fred A. Dusel III, Foreman Petersen Precision Engineering Co. Redwood City, CA
	K. Y. ROGERS, INC. 2670 E. Walnut Street Pasadena, CA 91107 Arranged by: (213) 681-3715 792-3165	• Five K.Y. Rogers, Inc. Machine Finish Specimans for Comparison Evaluation of Surface Finish on Machined Parts	

DOOR PRIZE PROGRAM RESULTS (continued)

PRIZE NO.	DONATOR	PRIZE	WINNERS
(58)	K.Y. ROGERS, INC. (continued)	• K.Y. Rogers, Inc. Machine Finish Speciman Approx retail value: $5.00	George M. Trinite, Branch Head USN Metrology Engineering Center Pomona, CA
(59)		• K.Y. Rogers, Inc. Machine Finish Speciman Approx retail value: $5.00	Wolf B. Egenter, Engineering Head Quality Engr. Test Establishment Ottawa, Ontario, Canada
(60)		• K.Y. Rogers, Inc. Machine Machine Finish Speciman Approx retail value: $5.00	Ralph E. Bertermann, Supervisor G. D. Searle Skokie, IL
(61)		• K.Y. Rogers, Inc. Machine Machine Finish Speciman Approx retail value: $5.00	Bill J. Allison, Gen. Supervisor Hughes Aircraft Co. Torrance, CA
(62)		• K.Y. Rogers, Inc. Machine Machine Finish Speciman Approx retail value: $5.00	Marvin G. Crown, Task Engineer Pacific Missile Test Center Pt. Mugu, CA
(63)	HONEYWELL, INC. 7037 Hayvenhurst Avenue Van Nuys, CA 91406 Arranged by: Bill Coe (213) 786-6416	• Leather Buxton Desk Set w/Calculator Approx retail value: $50.00	Keith Westover, Manager Intersil San Jose, CA

"WINNERS" HAD THEY NOT DECLINED!

DRAW		DRAW	
30th	Loebe Julie New York, NY	110th	Del Caldwell Claremont, CA

"WINNERS" HAD THEY ONLY BEEN THERE!

DRAW		DRAW	
5th	Larry Noe San Lorenzo, CA	13th	Dick Hubach Chatsworth, CA
14th	Steve Horland San Jose, CA	34th	Roberto Reyes Moorpark, CA
46th	Jim V. McDonald Sunny Vale, CA	49th	Bob Huenemann Mountain View, CA
50th	Jon Crickenberger Annandale, VA	58th	Charles B. Head Sunnymead, CA
59th	Glenn R. Crutchfield Washington, DC	60th	Norbert Laengrich Irvine, CA
62nd	Michael Flooa Xena, OH	63rd	William Harrison Sunnyvale, CA
65th	Robert Rickman San Pablo, CA	66th	Selden McKnight Heath, OH
68th	Victor Kunkel Santa Rosa, CA	69th	David Block Alta Loma, CA

"WINNERS" HAD THEY ONLY BEEN THERE!

DRAW		DRAW	
70th	Mike Schmahl San Jose, CA	71st	Glenn F. Engen Boulder, CA
72nd	Richard H. Anderson Los Altos, CA	74th	C. A. Gehrke Canoga Park, CA
75th	Dale Rush Huntington Beach, CA	77th	Gary DeZotell Canoga Park, CA
78th	Roderick D. Brimhall Perris, CA	80th	Larry Hodel Santa Clara, CA
82nd	Irving Gold Palo Alto, CA	85th	Alexander Zack Danvers, MA
86th	Evan Roberts Maple Valley, WA	88th	Thomas B. Miller Livermore, CA
89th	Lynn Hunt Santa Rosa, CA	91st	William M. Coe Van Nuys, CA
92nd	Sam Mingia Hayward, CA	93rd	Richard L. Katsch Milpitas, CA
94th	James T. Igoe Wappingers Falls, NY	95th	Brad Morgan San Jose, CA
96th	Robert Perry Rio Rico, AZ	98th	Jerry L. Newsome Riverside, CA
99th	Robert Mumma Bladensburg, MD	100th	Joe S. Kimes Lancaster, CA

"WINNERS" HAD THEY ONLY BEEN THERE!

DRAW		DRAW	
101st	Neil Faulkner Edmonds, WA	102th	Gary Smith Yuccipa, CA
104th	Bob Hesselberth Penfield, NY	106th	Ted Elick Warren, MI
107th	Carleton D. Bingham Argonne, IL	108th	Monty Jensen Mountain View, CA
109th	Bill Meyer Boise, ID	111th	Milton J. Lichtenstein Boonton, UT
112th	Jack Thurbon Montclair, CA		

MEASUREMENT SCIENCE CONFERENCE

DOOR PRIZE PROGRAM

4:00 p.m., Friday, January 21, 1983

(Palo Alto A and B Rooms)

Note to Attendees - Please read the following to assure that you will be eligible and ready to participate in this year's Door Prize Program. The prize you save may be your own!

1. All registered attendees*: Audience, Session Developers, Speakers and Exhibitor's Representatives are invited to participate; however, to be eligible to win you must:

   A. Complete and turn in your Conference Evaluation Questionnaire, and

   B. Be present at the Door-Prize Orawing.

   *(the 1983 MSC Board of Directors and Conference Committee have declared their members ineligible.)

2. The Door Prizes available for this year's Drawing are very exciting in terms of kind, quality and quantity (55 individual prizes having a total retail value of $8,954.90). This unique situation has been made possible by the graciousness of many individuals and various organizations through their contributions to our Door Prize Program. We have therefore listed the donators (in alphabetical order) along with their donations(s) so that they may be properly recognized.

3. Prizes will be drawn on a sequential first-call basis; therefore, due to the large number of prizes and the relatively short time available for the Drawing, it is suggested that you study the list of prizes and prioritize your personal choices in advance.

   NOTE: You will only have 30 seconds to state ywr selection by prize number; winners failing to make their selection within 30 seconds will be given a prize at random.

4. Prizes will be available for viewing in the Exhibits Area.

The Measurement Science Conference Board of Directors and Conference Committee wish each of you the best of luck at the Drawing. We sincerely hope that you enjoy the program and facilities organized for this year's Conference; and we urge you to plan on attending and participating in next year's Conference in the Southern California area.

Bob

Bob Couture,
Door Prize Chairman

Enclosure: Door Prize Listing

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Abbott, E. V.
Sr. Eng. Spec.
Vought Corporation
P. 0. Box 225907
Dallas, TX 75265
214-266-4960

Abeyta, Marcus
Metrology Supervisor
Ford Aerospace
Bldg. 8, Room 26
Newport Beach, CA 92683
714-720-4821

Agy, Dave
Product Specialist, Sr.
John Fluke Mfg. Co., Inc.
P. 0. Box C9090
Everett, WA 98206
206-356-5471

Alderton, Philip C.
Marketing Manager
Instrulab, Inc.
P. 0. Box 98
Dayton, OH 45404
513-223-2247

Allison, William J.
Gen. Sup.-Power Tube Dept.
Hughes Aircraft
P. 0. Box 2999
Torrance, CA 90509
213-517-5180

Anderson, Richard H.
Project Leader-Sensor Develop.
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Dept. 62-12, Bldg. 151
Sunnyvale, CA 94086
408-742-6362

Andrew, James F.
Staff Member, MST-13
Los Alamos National Lab.
M/S E511, Group MST-13
Los Alamos, NM 87545
505-667-2318

Armann, Dean
Sales Manager
Pacific Measurements, Inc.
488 Tasman Dr.
Sunnyvale, CA 94036
408-734-5780

Armbruster, Keith
Sales
True Time
3484 Stevens Creek Blvd.
San Jose, CA 95117
408-554-0455

Bailey, George M.
Vice President
Science Applications, Inc.
1735 Jefferson Davis Hwy. #907
Arlington, VA 22202
703-979-2830

Baker, C. H.
MTS Metrology
Rockwell International
3370 Miraloma Ave.
Dept. 120
Anaheim, CA 92803
714-632-3923

Baldock, Paul
Project Manager
John Fluke Mfg. Co., Inc.
P. 0. Box C9090
Everett, WA 93206
206-356-5546

Balkon, Charles
Sr. Lab. Spec./K22
I.B.M.
5600 Cottle Rd.
San Jose, CA 95193
403-256-3434

Banek, Reinhold
Co-Owner
Grover Gulch Winery
1557 Day Valley Rd.
Aptos, CA 95003
408-688-4335

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Banning, Harmon
V.P. Engineering
Weinschel Engineering
One Weinschel Lane
Gaithersburg, MD 20760
301-948-3434

Bassano, Dennis
co-owner
Grover Gulch Winery
7880 Glen Haven Rd.
Soquel, CA 95073
408-475-0568

Beason, Dave
Vice President
Jay Stone & Assoc.
339 S. San Antonio Rd.
Los Altos, CA 94022
415-948-4563

Beckert, G. F.
Engineer
Computer Sciences Corp.
MS-330
Arnold AFS, TN 37389
615-455-2611, X7406

Belanger, Brian C.
Chief, Off. of Meas. Services
U.S. National Bureau of Standards
Bldg. 362 - Piiys. Bldg.
Washington, DC 20234
301-921-2805

Belecki, Norman B.
Elec. Meas. & Stds. Div.
National Bureau of Standards
Bldg. 146, MET
Washington, DC 20234
301-921-2715

Bendit, Philip
Mech. Eng.
DOD MEC
6020 Eastwood
Alta Loma, CA 31701
714-989-3442

Bertermann, Ralph
Real Time Systems
G. D. Searle Co.
4901 Searle Parkway
Skokie, IL 60077
312-982-7609

Bicksler, Ralph
Qual. Engr./Qual. Assur.
Memorex
San Tomas at Central
Santa Clara, CA 95052
408-987-1769

Biller, Bob
Marketing Manager
Micr-Tel Corp.
6310 Blair Hill Lane
Baltimore, MD 21209
301-823-6227

Bingham, Carleton D.
Dir., New Brunswick Lab.
U.S. Dept. of Energy
9800 So. Cass Ave.
Argonne, IL 60439
312-972-2446

Birnbaum, Joel S.
Director, Adv. Computer Labs.
Hewlett-Packard
Palo Alto, CA 94304

Blackburn, Chuck
Sales Manager
Wahl Instruments
5750 Hannum Ave.
Culver City, CA 90230
213-641-6931

Blackman, Howard
Western Regional Manager
Electro Rent Corp.
4131 Vanowen Place
Burbank, CA 91505
213-843-3131

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Bleasdale, Gene
Appl. Engineer
Dale-Dahl Assoc.
2363 Blvd. Circle
Walnut Creek, CA 94595
415-933-9595

Block, David R.
QA Spec./Strategic Wea. Sys.
Fleet Analysis Center
FLTAC 8612
corona, CA 91720
714-736-4461

Bonis, Scott A.
Act. Mgr., Met. Engineering
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Dept. 48-72. Bldg. 182
Sunnyvale, CA 94086
408-742-5180

Bowling Jr., Louie R.
Elec. Eng.-Primary Lab.
U.S. Army TMDE Support Grp.
DRXTM-SM
Redstone Arsl., AL 35898
205-876-8417

Bowman, John
Sales Engineer
John Fluke Mfg. Co.
20901 Bonita St.
Carson, CA 90746
213-538-3900

Bradshaw, Andy
Rockwell International
1225 North Alma Rd.
Richardson, TX 75081
214-996-6074

Brady, John
Associate Professor
Orange Coast College
2701 Fairview Rd.
Costa Mesa, CA 92626
714-556-5761

Brimhall, Rod
Hughes-Fullerton
20911 Mural St.
Perris, CA 92370
714-732-5786

Brink, Larry E.
Dir., Winemaking & Blending
Paul Masson Vineyards
13150 Saratoga Ave.
saratoga, CA 95070
408-257-7800

Broderick, Jim
Area **Manager**
Electrorent
2230 Charleston Rd.
Mountain View, CA 94043
415-964-5500

Broschinsky, Ronald
Q. E.. Metrology
Brunswick Corp.
3333 Harbor Blvd.
Costa Mesa, CA 92626
714-546-8030 x6449

Browne, William
Vice Pres.-Sales/Marketing
Marotta Scientific Controls, Inc.
1500 Boonton Ave.
Boonton, NJ 07005
201-334-7800

Brungart, Dean A.
Metrology Director
Teledyne Systems Co.
19601 Nordhoff St.
Northridge, CA 91324
213-886-2211, X2601, 2602

Buck. Dave
Supervision
Lockheed California Co.
Bldg. 322, B-6
Burbank, CA 91520
213-847-5095

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Burdge, Kevin
Marketing Manager
Hart Scientific
54 N. 400 W.
Provo, UT 04601
801-375-7221

Burger, Chris
Prof.
Iowa State University
Dept. Engr. Sci. & Mech.
Ames, IO 50011
515-294-5853

Bush, Rick
V.P. Sales
EIP Microwave
2731 No. First St.
San Jose, CA 95134
408-946-5700

Bushnell, Ralph
Supervisor, Elect. Sec.
NARF Alameda
Navy Stds. Lab., Code 662
Production Engineering, Code 660
Alameda, CA 94501
415-869-3137

Caldwell, Del
Division Manager
Navy Met. Eng. Cntr.
P. 0. Box 2436
Pomona, CA 91769
714-620-0525

Cannell, Geoff
Chairman of the Board
DATRON
3401 S.W. 42nd St.
Stuart, FL 33494
305-233-0935

Carlton, Leslie W.
QA Manager
GIDEP
GIDEP Operations Center
Corona, CA 91720
714-736-4470

Carrington, Ken
Section Manager
Computer Sciences Corp.
MS-330
Arnold AFS, TN 37389
615-455-2611, X7291

Carroll, Jack H.
Sr. Inspec. Spec.
Hewlett-Packard
P. 0. Box 301
Loveland, co a0537
303-667-5000 x3562

Carroll, Robert E.
Sr. Insep. Spec.
I.B.M.
5600 Cottle Rd.
San Jose CA, CA 95193
408-256-6545

Carver, Lloyd A.
Piiysical Lab. Supervisor
Simco
382 Martin Ave.
Santa Clara, CA 95050
408-727-3611

Cauffman, David P.
Mgr., Meas. Std. Labs.
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Dept. 48-71, Bldg. 151
Sunnyvale, CA 94086
408-743-1800

Cegelski, Charles
QA Engineering
Applied Technology
645 Almanor Ave.
Sunnyvale, CA 94036
408-732-2710, X2174

Chlupsa, J. Matt
Senior Engineer
RFL Industry
Powerville Rd.
Boonton, NJ 07005
201-334-3100, X280

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Christopher, Amber
Marketing Comm. Coord.
U.S. Instrument Rentals
2988 Campus Drive
San Mateo, CA 94403
415-572-6682

Clark, Kevin
Vice President, Marketing
Valhalla Scientific
7576 Trade St.
San Diego, CA 92071
619-578-8280

Cleary, Ken
Metrology Specialist
American Heyer-Schultz
600 Pine Ave.
Goleta, CA 93117
805-967-3451, X468

Coe, William M.
Branch Service Manager
Honeywell, Inc.
7037 Hayvenhurst Ave.
Van Nuys, CA 91406
213-786-6410

Collier, Warren
Corp. QA Metrology & Standards
Tektronix, Inc.
P. 0. Box 500, 78-528
Beaverton, OR 97077
503-627-1678

Conway, Marty
Vice President-Marketing
Volumetrics
634 Airport Rd.
Paso Robles, CA 93446
805-235-0110

Cornejo, Robert E.
Sr. Inspector, 327
I.B.M.
5600 Cottle Rd.
San Jose, CA 95193
408-256-6544

Corrigan Jr., M. J.
IML Manager
Lockheed Electronics Center
1501 U.S. Highway 22
Plainfield, NJ 07063
201-757-1600, X2734

Cortis, Stephen N.
U.S. Army Tank-Auto Command
28251 Van Dyke Ave.
Warren, MI 48090
313-574-6493

Couture, Robert J.
Manager, Metrology Engineering
Rockwell International
3370 Miraloma Ave.
Dept. 120
Anaheim, CA 92803
714-632-3923

Crane, Chet
Metrology Manager
Teledyne Microelectronics
12964 Panama St.
Los Angeles, CA 90066
213-822-8229

Crickenberger, Jon
Mechanical Engineer
Navy Primary Stds. Lab
Washington Navy Yard, Bldg. 291-2
Washington, DC
202-433-3012

Crisologo, Ernie
Technical Manager
Viking Lab
440 Bernardo Ave.
Mountain View, CA 94043
415-969-5500

Crites, Dale
Sales Engineer
Ward/Davis Associates
3329 Kifer Rd.
Santa Clara, CA 95051
408-245-3700

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Crittenden, Hal
Vice President
Jay Stone & Assoc.
339 s. San Antonio Rd.
Los Altos, CA 94022
415-948-4563

Crown, Marvin G.
Electronics Engineer
Pacific Missile Test Center
Code 3530
Metrology Division
Point Mugu, CA 93042
805-982-7926

Crutchfield, Glenn R.
Engineering Tech. (Mech.)
Navy Primary Stds. Lab
Washington Navy Yard, Bldg. 219-2
Washington, DC

Cuevas, Mike
Product Manager/Marketing
Hewlett-Packard
1501 Page Mill Rd.
Palo Alto, CA 94304
415-857-2047

Cuff, S. P.
General Manager
Calex Mfg. Co., Inc.
3355 Vincent Rd.
Pleasant Hill, CA 94523
415-932-3911

Dahl, Fred
Appl. Engineer
Dale-Dahl Assoc.
2738 W. Main St.
Alahambra, CA 91103
213-682-3417

Daneman, H. L.
HLD Associates
1304 Calle Ramon
Santa Fe, NM 87501
505-983-5883

Davis, Chuck E.
Sup., Mech. & Struc. Insp.
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Dept. 75-42. Bldg. 15H
Sunnyvale, CA 94086
408-742-0741

Davis, David L.
Raw Materials Group Leader
American McGaw
P. 0. Box 11837
Santa Ana, CA 92711
714-660-2868

De Zotell, Gary
Engineering Manager
View Engineering
9736 Eton Ave.
Chatsworth, CA 91311

Dea, Patsy
Measurement Engineering
TRW
One Space Park
Bldg. S/Rm. 2470
Redondo Beach, CA 90273
213-535-2445

Dear, Fred
Capt.
U.S. Marine Corps.
P. 0. Box 2436
Liaison Office NWS Seal Beach
Pomona, CA 91769
714-620-0530

Dever, James F.
Group Eng./Flt. Test Eng.
Boeing
3507-NE 93rd St.
Seattle, WA 98115
206-655-2211

Dishmon. John
Sales Representative
Basic Systems
2359 De La Cruz Blvd.
Santa Clara, CA
408-727-1800

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Dockswell, Sheldon
Technical Director
Mantech International
8352 Clairmont Mesa Blvd.
San Diego, CA 92111
619-292-9000

Doty, Don
Vice President
Jay Stone & Assoc.
339 S. San Antonio Rd.
Los Altos, CA 94022
415-948-4563

Druhe, Dennis
National Sales Manager
Luxtron
1060 Terra Bella
Mountain View, CA 94043
415-962-8110

Duca, Nick
Sales Rep.
U.S. Instrument Rentals
700 S. Claremont
San Mateo, CA 94402
415-579-0911

Duggins, J. C.
sup., Data & Calib. Require.
Vought Corporation
P. 0. Box 225901
Dallas, TX 75265
214-266-3592

Duncan, Clifford F.
Instrumentation Eng. Sr.
Lockheed Missiles & Space Co., Inc.
P. 0. Box 6492, NSB Bangor
Bremerton, WA 98315
206-396-4388

Dunning, Warren
Instrumentation Engineer
Explosive Technology
P. 0. Box KK
Fairfield, CA 94533
707-422-1880, X70

Dusel, F.
Foreman
Petersen Prec. Engr.
611 Broadway
Redwood City, CA 94063
415-365-4373

Dwyer, Steve
Reliability Analyst
Metrology Engineering Center
3036 Lees Ave.
Long Beach, CA 90808

Eckels, Calvin
Engineer
Argo Systems
884 Hermosa Ct.
Sunnyvale, CA 94086
408-737-2000, X2574

Edwards, Eugene
Engr., Calib. TMDE Group
U.S. Army Calibration
Bldg. 5435, Redstone Arsenal
DRXTM-SP
Redstone Arsl., AL 35898
205-876-3631

Egenter, Wolf
Head, Stds. & Tribology Lab.
National Defence-Canada
Quality Eng. Test Establishment
Ottawa, ON Canada K1A-OK2

Einstein, Brad J.
Manager, Stds. & Calib.
Northrop-Electronics Division
2301 W. 120th St. 8221/A60
Hawthorne, CA 90250
213-418-4466

Elick, Ted
U.S. Army Tank-Auto Command
Warren, MI 48090
313-574-6789

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Elliott, Brian
Research Engineer
Hewlett-Packard
1501 Page Mill, Bldg. 3L
Palo Alto, CA 94304

Ellis, R. W.
Sup., Stds. & Calib. Labs.
EG & G Idaho, Inc.
P. 0. Box 1625, CFA 698
Idaho Falls, ID 83415
208-526-2656

Endsley, Ross
Standards Engineer
Union Carbide Corp.
Box Y, Bldg. 9737
Oak Ridge, TN 37830
615-574-0527

Engen, Glenn F.
Physicist, Microwave Met. Grp.
National Bureau of Standards
325 Broadway, 724.01
Boulder, CO 80303
303-497-3511

England, R. B.
Group Eng./Meas. Control
General Dynamics
P. 0. Box 2507
Pomona Division, MZ 2-60
Pomona, CA 91769
714-620-2511, X4745

Erickson, Gerald A.
QA Supv./Central Labs.
TVA
1734 Lakewood Circle
Hixson, TN 37343
615-697-4294

Evans, Leslie R.
Senior Vice President
Electro Rent Corp.
4209 Vanowen Place
Burbank, CA 91505
213-843-3131

Farnsworth, Hal
Telecommunication Sales
EIP Microwave
2731 No. First St.
San Jose, CA 95134
408-946-5700

Faulkner, Neil
Sr. Design Engineer
John Fluke Mfg. Co., Inc.
P. 0. Box C9090
Everett, WA 98206
206-356-5538

Faunce, Denis
Supervisor-Metrology
Ford Aerospace
Ford Rd. 6-141
Newport Beach, CA 92660
714-760-2995

Featherstone. Walt
Featherstone Associates
2041 Pioneer Ct.
San Mateo, CA 94403
415-345-1617

Ferrera, Tony
Supervisor-Technical Services
SRI International
333 Ravenswood - MS 20241
Menlo Park, CA 94025
415-859-4001

Fitzpatrick, Jim
Product Manager
Hewlett-Packard
1400 Fountain Grove Parkway
Santa Rosa, CA 95404
707-525-1400

Fleming, Guy J.
Supervisor, Main. & Cal. Lab.
United Technologies
P. 0. Box 358
Chemical Systems Div.
Sunnyvale, CA 94086
408-778-4270

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Flora, Michael
Sales Assistant
Yellow Springs Instrument
P.O. Box 465
Yellow Springs, OH 45387
513-767-7241

Foley, Dennis L.
QC Gen. Supervisor
Ivac Corp.
10300 Campus Pt. Drive
Inspection/Process Control
San Diego, CA 92121
619-457-7006

Fong, Reg
Branch Head, Navy Stds. Lab.
NARF Alameda
Navy Stds. Lab., Code 662
Production Engineering, Code 660
Alameda, CA 94501
415-869-3137

Fontanella, Odi
Sales
Metermaster
3995 E. Bayshore Rd.
Palo Alto, CA 94303
415-968-0313

French, Judson C.
Director
National Bureau of Standards
Bldg. 220, Rm. B358
Ctr. for Elec. & Elec. Engrg.
Washington, DC 20234
301-921-3357

Fry, W.R.
Project Engineer
GIDEP Operations Center
Officer-in-Charge, Attn: W. R. Fry
Corona, CA 91720
714-736-4677

Fuellenbach, Art
Full-Time Student
San Jose State Univ.
39490 N. # Albany Common
Fremont, CA 94538
415-793-9950

Gangawer. Bob
Applications Engineer
Guildline Inst., Inc.
2 Westchester Plaza
Elmsford, NY 10523
914-592-9101

Gardner, Leonard B.
Consultant
Automated Integrated Manufacturing
2406 Buttetop Place
Spring Valley, CA 92078
619-464-2446

Gargyi, Gyula
Sales Eng.
John Fluke Mfg. Co.
19663 Pine Valley Ave.
Northridge, CA 91326
213-538-3900

Geesaman, Robert J.
Section Head, Elect. Stds.
Hughes Aircraft
Centinella & Teale Sts.
Culver City, CA 90230
213-305-2427

Gehrke, C. A.
Field Service
View Engineering
9736 Eton Ave.
Chatsworth, CA 91311
215-998-4230, X24

Geremia, John 0.
Prof., M. E.
U.S. Naval Academy
Annapolis, MD 21402
301-267-3583

Glassett, Walter L.
Supervisor, Test Engineering
Sundstrand Data Control, Inc.
Overlake Industrial Park, MS 19
Redmond, WA 98052
206-885-8050

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Gleason, Eugene A.
Micro-Surface Eng.
15034 Loft Hill Rd.
La Mirada, CA 90638

Gold, Irving
Appl. Engr.
Basic Systems Corp.
2359 De LA Cruz Blvd.
Santa Clara, CA 95050
408-727-1800

Gonzalez, Henry
Project Leader
U.S. Army White Sands Missile Range
Attn: STEWL-LG-CS, U. S. Army WSMR
WSMR, NM 88002
505-678-1825

Goodhead, David D.
President
Westcon, Inc.
5101 N. Interstate Ave.
Portland, OR 97217
503-283-0132

Graef, Edgar L.
Elect. Tech
Dept. of Navy
N8SD-E Washington Navy Yard
Navy Primary Standards
Washington, DC 20378

Greb, Donald J.
Consultant
3754 De Sabla Drive
Cameron Park, CA 95682
916-677-9612

Greene, Rick
Sr. Metrologist Spec.
I.B.M.
5600 Cottle Rd.
Dept. 358/001
San Jose, CA 95193
408-256-3305

Greenwood, Steve
Crystal Engineering
1216 2nd St.
LOS Osos, CA 93402
805-528-2155

Gregersen, Chuck
Insp. Spec. 327
I.B.M.
5600 Cottle Rd.
San Jose, CA 95193
408-256-6545

Gross, Paul
Technical Director
U.S. Navy
Naval Electronic Systems Command
Test & Monitoring Sys. Program Office
Washington, DC 20363
202-692-0170

Grosser, James A.
QC Manager
K. Y. Rogers, Inc.
2670 East Walnut
Pasadena, CA 91107
213-792-3165

Gucciardo, Richard
Grumman Aerospace
S. Oyster Bay Rd., #B05-31
Bethpage, NY 11714

Gutierrez, Reuben L.
Staff Member Inspection
Los Alamos National Lab.
P. 0. Box 1663, MS E511
Los Alamos, NM 87545
505-667-2323

Halaczkiewicz, Tom
Crystal Engineering
1216 2nd St.
LOS osos, CA 93402
805-528-2155

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Halford, Ken
Metrology Engineer
Litton Data Systems
8000 Woodley Ave. MS 43-87
Van Nuys, CA 91409
213-902-4268

Hall, Jack
Metrologist
Rockwell International
3370 Miraloma Ave. MC HC02
Anaheim, CA 92803
714-632-3923

Hamilton, Larry W.
Manager, Quality
Shiley, Inc.
17G00 Gillette Ave.
Irvine, CA 92714
714-850-8254

Hanford, J. J.
Mktg. Asst.
Ectron Corporation
8159 Engineer Rd.
San Diego, CA 92111
619-278-0600

Hanford, W. W.
Vice President
Ectron Corporation
8159 Engineer Rd.
San Diego, CA 92111
619-278-0600

Harkness, Jr., Ashley
Calibration Laboratory Spec.
Electro Test, Inc.
P. 0. Box 159
San Ramon, CA 94583
415-820-5666, X310

Haro, Peter J.
Branch Chief
NASA, Ames Research Center
MS 213-6
Moffett Field, CA 94035
415-965-5468

Harrison, Wm.
Metrology Eng.
Applied Technology
G45 Almanor Ave.
Dept. 4150
Sunnyvale, CA 94086
408-732-2710, X2174

Hayes. Jerry L.
Metrology Technical Director
Naval Weapons Station
1675 W. Mission Blvd.
Seal Beach, Pomona Annex
Pomona, CA 91769
714-620-0500

Haymes, Harry B.
Manager, Standards Lab.
Sanders Associates, Inc.
95 Canal St., NCA L-0137
Nashua, NH 03061
603-885-4913

Head, G. B.
QA Specialist/Meas. Control
General Dynamics
P. 0. Box 2507
Pomona Division, MZ 2-60
Pomona, CA 91769
714-620-7511, X8280

Hedrich, Albert L.
Sr. Engineer
National Bureau of Standards
Sound - Al49
Washington, DC 20234
301-921-3646

Heinz, Sue Jean
Engineering Technician
Abbott Laboratories
1400 Sheridan Rd.
North Chicago, IL 60064
312-937-4918

Hensley, Otis
Group Supervisor, Meas. Ctrl.
General Dynamics-Convair
P.O. Box 85357 MZ 43-3630
San Diego, CA 92138
619-277-8900, X2294

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Hesselberth, R. J.
President
Spectracom Corp.
320 N. Washington St.
Rochester, NY 14625
716-381-4827

Hirst, Michael
Vice President
Hart Scientific
54 N. 400 W.
Provo, UT 84601
801-375-7221

Hodel, Larry
Area Manager
Basic Systems
2359 De La Cruz Blvd.
Santa Clara, CA 95050
408-727-1800

Holden, William F.
Mfg. Technology Program Office
HQ Naval Material Command
Mat 064
Washington, DC 20360
202-692-0121

Honea, Don
Sales
Meter-master
3995 E. Bayshore Rd.
Palo Alto, CA 94303
415-968-0313

Hook, James J.
Head, Ocean Systems Div.
Fleet Analysis Center
Corona, CA 92666
714-736-4469

Hopping, Dave
Metrology Manager
Hewlett-Packard
1400 Fountain Grove Parkway
Santa Rosa, CA 95401
707-525-1400, X2148

Houston, M.
Mfq. Sup./Meas. Control
General Dynamics
P. 0. Box 2507
Pomona Division, MZ 2-60
Pomona, CA 91769
714-620-7511, X3330

Hubach, Richard
President
View Engineering
9736 Eton Ave.
Chatsworth, CA 91311
213-998-4230

Humphrey, D. G.
Group Eng./Meas. Control
General Dynamics
P. 0. Box 2507
Pomona Division, MZ 2-60
Pomona, CA 91769
714-620-7511, X4319

Hunt, Lynn
Test Equipment Maintenance
Hewlett-Packard
1400 Fountain Grove Parkway
Santa Rosa, CA 95401
707-525-1400, X2946

Hustinq, N. E.
Training Supervisor
Bechtel Power Corp.
50 Beale St., 1MKP/15/A-8
Supplier Quality Dept.
San Francisco, CA 94553
415-768-8479

Igoe, James T.
Sr. Lab Spec.-125
IBM
Bldg. 330
Hopewell Jct., NY 12533
914-897-4887

Ingram, Jr., James M.
National Service Manager
U.S. Instrument Rentals
2988 Campus Dr.
San Mateo, CA 94403
415-572-6756

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Irvine, Robert G.
Assoc. Prof./ECE Dept.
Cal Poly University
3801 W. Temple Ave.
Pomona, CA 91768
714-598-4542

Ivey, William G.
Section Head, CSD
TRW
One Space Park
Redondo Beach, CA 90278
213-535-3380

Jarzombek, Rusty
Metrology Manager
TRW Microwave, Inc.
825 Stewart Drive
Sunnyvale, CA 94086
408-732-0880, X345

Johnson, Eugene E.
Head, Testing Branch
Naval Sea Systems Command
Washington, DC 20362
202-692-7748

Johnson, Henry M.
JTCG-METCAL R&D Rep.
USAF
HQ. AFSC
Andrews AFB, DC 20334
301-981-4913

Johnson, Mel
Sales Engineer
Solartron
17972 Sky Park Circle
Irvine, CA 92714
714-641-7137

Johnson, Ronald A.
Tech. Trainer
FMC Corp.
1125 Coleman Ave., Box 367, MS MO8
Employee Development Dept.
San Jose, CA 95103
301-948-7550, X208

Johnson, Thomas
Head, Metrology Service
Watkins-Johnson
700 Quince Orchard Rd.
Gaithersburg, MD 20378
301-948-75550, X203

Johnstone, Richard
Head, Metrology Engineering
Hughes Aircraft
Centinella & Teale Sts.
Culver City, CA 90230
213-305-2290

Julie, Loebe
President
Julie Research Laboratories, Inc.
211 West 61st St.
New York, NY 10023
212-245-2727

Kamerkink, Ron
President
Novus

Katsch. Richard L.
Elect. Stds. Engr.
Simco
382 Martin Ave.
Santa Clara, CA 95050
408-727-3611

Kaufman, Mark
R&D Engineer/QA
FACC
Ford Rd., Bldg. 6
Newport Beach, CA 92660
714-760-2934

Kellick. Ray
Manager, Elec. Calib.
Teledyne Systems Company
19601 Nordhoff St.
Northridge. CA 91364
213-886-2211, X2509

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Kessel, David R.
Manager, Calibration Lab.
RCA "Selecta Vision" Video Disc. Ops.
P. 0. Box 91079
Indianapolis, IN 46291
317-273-3076

Killmeyer, Herman J.
Newark Air Force Station
834 Larkspur Dr.
Newark, OH 43055
614-345-6268

Kimes, J. S.
Sup./Quality Assurance
Rockwell International
42849 Cherbourg Ln.
Lancaster, CA 93534
805-272-4370

King, Jr., W. L.
Metron Corp.
9681 Business Center Drive
Ran. Cucamonga, CA 91730

Kirkpatrick, Brent
SUP., Electrical Standards
Teledyne Systems Company
19601 Nordhoff St.
Northridge, CA 91324
213-886-2211, X2525

Klinger, John H. (Jack)
Mktg. Eng.-Marketing Dept.
Hewlett-Packard
5301 Stevens Creek Blvd.
Santa Clara, CA 95050
408-246-4300, X2579

Koep, Dennis M.
V.P., Sales
Standard Reference Labs., Inc.
Coan Place, P.O. Box 388
Metuchen, NJ 08840

Koide, Frank K.
Sr. Project Engineer
Rockwell International
3370 Miraloma Ave. MC HC02
Anaheim, CA 92803
714-632-3923

Koop, Clifford D.
Manager
Rockwell International, 137-152
P. 0. Box 728
Cedar Rapids, IA 52498
319-395-5554

Kottman, R.
Eng. Tech., Tool Eng.
Abbott Laboratories
1400 Sheridian Rd.
North Chicago, IL 60064
312-937-3756

Ku. Alick C. C.
Mgr., Compliance Programs/RCD
American Hospital Supply Corp.
One American Plaza
Evanston, IL 60201
312-866-4123

Kunkel, Victor
Appl. Eng.
True Time Instruments
3243 Santa Rosa Ave.
Santa Rosa, CA 95401
707-528-1230

Kuntze, Robert E.
Mechanical Metrology
Hewlett-Packard
1501 Page Mill Rd.
Palo Alto, CA 94304
415-857-2565

Kwan, Bill
Sales Engr.
Hewlett-Packard
1424 Fountain Grove Parkway
Signal Analysis Division
Santa Rosa, CA 95401
707-525-1400

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Kychakoff, George
Res. Asst. Mech. Eng.
Stanford University
Dept. of Mech. Engr.
Stanford, CA 94305
415-497-1823

Laengrich, Norbert
Sales Manager
Racal-Dana
4 Goodyear St.
Irvine, CA

Lance, Algie L.
Senior Scientist
TRW-Operations & Support Group
S-2470. One Space Park
Redondo Beach, CA 90278
213-535-5155

Lange, Paul R.
Cmdr. AGMC
USAF
AGMC, Heath
Ohio, OH
614-580-7335

Langerich, Norbert
Marketing Manager
Racal-Dana
4 Goodyear St.
Irvine, CA 92714
408-727-2341

Larson, Robert E.
President
Systems Control, Inc.
Palo Alto, CA

Lay, Maynard D.
Chief, Systems Metrology Div.
Aerospace Guidance & Metrology Center
AGMC/MLS
Newark AFS, OH 43055
614-522-7788

Lee, John J.
Sr. Vice President/Operations
U.S. Instrument Rentals
2988 Campus Drive
San Mateo, CA 94403
415-572-6730

Lee, Jr., John J.
Electra-Optical Physicist
General Dynamics Convair
P. O. Box 80847, MZ 43-3630
San Diego, CA 92138
619-277-8900, X1640

Leeb, Len
Mktg. Engineer
Hewlett-Packard
1501 Page Mill Rd.
Palo Alto, CA 94304
415-857-3320

Lentner, Keith J.
National Bureau of Standards
Met., Bldg. 162
Washington, DC 20234
301-921-2727

Lewis, John
Supv. Electronic Engineer
Navy FLTAC
Code 8242
Corona, CA 91720
714-736-5227

Lewis, Rollin
Lab Tech I, Tech. Services
Orcon Corporation
33430 Western Blvd.
Union City, CA 94587
415-489-8100

Lichtenstein, Milt
Vice President, Marketing
Ballantine Labs
90 Fanny Rd.
Boonton, NJ 07005
201-335-0900

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Lillard, Ray
Systems Engineer
John Fluke
2300 Walsh Ave.
Santa Clara, CA 95051
408-727-0513

Linerud, Cornell B.
Mgr., Elec. Test, Insp. & PAL
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Dept. 75-44, Bldg. 151
Sunnyvale, CA 94086
408-742-3423

Logue, Tom
Standards Lab Supervisor
Hewlett-Packard
1400 Fountain Grove Parkway
Santa Rosa, CA 95404
707-525-1400, X2988

Lorenzen, David A.
Metrology Engineer
McDonnell Douglas Astronautics Co.
5301 Bolsa Ave.
Huntington Bch., CA 92946
714-896-4574

Lund, Kenneth J.
Metrologist
Rockwell International
3370 Miraloma Ave., MC HC02
Anaheim, CA 92803
714-632-3923

Maines, Roy
Sales Manager
PCB Piezotronics, Inc.
3425 Walden Ave.
Depew, NY 14043
716-684-0001

Martin, John T.
Manager, Test Reliability
Westinghouse NTD
P. 0. Box 855
Forest Hills Site
Pittsburgh, PA 15230
412-829-3703

Marxer, Dean
Sales Engineer
Cutlass Electronics
1803 Iowa St.
Costa Mesa, CA 92626
714-549-9358

Mason, Gerald W.
Sr. Spec.-Electronic Eng.
United Technologies
P. 0. Box 358
Chemical Systems Div.
Sunnyvale, CA 94086
408-778-4453

Maurer, Bill
Test Engineer
Apple Computer, Inc.
20525 Mariani Ave.
Cupertino, CA 95014
408-973-3470

McCoubrey, Aurthur
Assoc. Dir. for Meas. Serv.
National Bureau of Standards
Washington, DC 20234
301-921-3301

McDonald, Jim V.
Sales #751
Esterline-Angus
563 E. Lewelling Blvd.
San Lorenzo, CA 94580
415-278-4502

McDonell, Duncan F.
Mech. Eng., Metrology Division
Pacific Missile Test Center
Code 3533
Point Mugu, CA 93042
805-982-7783

McKitrick, Byron S.
Mgr., Electronic Maintenance
Hewlett-Packard
3404 E. Harmony Rd.
Ft. Collins, co a0525
303-226-3800, X2079

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

McKnight, Selden
Director, Metrology
U.S. Air Force
Newark AFS, AGMC/ML
Newark, OH 43055
614-522-7450

McNamara, Gary
Sales Manager
Weinschel Engineering
29169 Heathercliff Rd.
Malibu, CA 90265
213-457-4563

McSparron, Donald
Physicist
National Bureau of Standards
RM B306, Bldg. 220
Washington, DC 20234
301-921-3613

Meadows, James
Sr. Tech. Trainer
FMC Corp.
1125 Coleman Ave., Box 367, MS MO8
Employee Development Dept.
San Jose, CR 95103
408-289-2335

Meyer, Bill
Metrology Manager
Hewlett-Packard
P. 0. Box 15
Boise, ID 83707
208-376-6000, X2221

Milburn, John
Lead-Instrumentation Dept.
Watkins Johnson
2525 No. First St.
San Jose, CA 95131
408-262-1400, X332

Miller, Charles K. S.
Chief
National Bureau of Standards
325 Broadway, MC 723.00
Electromagnetic Fields Division
Boulder, CO 80303
303-497-3131

Miller, Gary L.
Section Chief, QC Insp.
United Technologies
P. 0. Box 358, MS 0201/101
Chemical Systems Div.
Sunnyvale, CA 94086
408-778-4330

Miller, J. R.
Physicist
U.S. Army Calibration
P. 0. Box 2351, MS 13
DRXTM-SP
Redstone Arsl., AL 35802
205-876-2876

Miller, Richard
EO Systems Program Manager
Science Applications, Inc.
P. 0. Box 2351, MS 13
La Jolla, CA 92038
619-456-6531

Miller, Thomas B.
Eng. Engineering Measurements
Lawrence Livermore National Lab.
P. 0. Box 808
Livermore, CA 94550
415-422-7041

Mills, F. M.
Supervisor, Metrology Lab.
FMC Corp. Ordnance Div.
1125 Coleman Ave., Box 367
San Jose, CA 95103
408-289-2748

Minck, John L.
ADSP Manager
Hewlett-Packard
1501 Page Mill Rd.
Palo Alto, CA 94304
415-857-2060

Mingia, Sam
Sales Engineer
FLW
31162 San Clemente
Hayward, CA 94544
415-487-2222

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Miracle, Jim
Sales Engineer
FLW
31162 San Clemente
Hayward. CA 94544
415-487-2222

Mitchell, J. David
Director of Adv. Prog. & Mfg.
Rockwell International
Pittsburgh, PA

Monroe, Robert
Director, Test Tech. Inf. Ctr.
U.S. Navy, FLTAC
Corona, CA 91720
714-736-5227

Mordecai, Lionel
Supervisory Engineer
Navy Primary Standards
Naval Air Rework Fac., North Island
San Diego, CA 92135
619-437-6991

Morgan, Brad
West Coast Reg. Sales Mgr.
Norland Corp.
Rt. 4. Norland Drive
Ft. Atkinson, WS 53538
414-972-2244

Morrison, Kenneth D.
Supervisor, Metrology
Northrop Corp.
500 East Orangethorpe Ave.
Electra-Mechanical Div., Dept. 6653
Anaheim, CA 92801
714-371-5000, x443

Moser, Elliot
Sr. Vice President
Rusks. Instrument
Box 36010
Houston, TX 77236
713-975-0547

Mowry, Bill
Sales Engineer
Racal-Dana
4 Goodyear St.
Irvine, CA 92714
408-727-2341

Mukaihata, Tad
Manager, Primary Standards
Hughes Aircraft Co.
Bldg. 20, MS X125
Culver City, CA 90230
213-305-2287

Mumma, Robert
Engineering Tech.
Navy Primary Standards. Lab.
Washington Navy Yard, Bldg. 219-2
Washington, DC 23817
202-433-3012

Munier, Arthur M.
Chief, Calibration Office
Jefferson Proving Ground
Madison, IN 47250
812-273-7146

Nanzetta, Philip
Senior Mathematician
National Bureau of Standards
Automated Production Technology Div.
Washington, DC 20234
301-921-2577

Nelson, John
Mech. Engr.
Navy Metrology Engr. Center
P. 0. Box 2436
Pomona, CA 91769
714-620-0561

Nelson, Robert E.
Asst. Chief, Elec. Tech. Div.
National Bureau of Standards
325 Broadway
Boulder, CO 80303
303-497-5736

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Nemeroff, Edward
Vice-President, Sales
Guildline Inst., Inc.
2 Westchester Plaza
Elmsford, NY 10523
914-592-9101

Newsome, Jerry L.
Elect. Tech-RF Microwave
Navy Stds. Lab.
P. O. Box 2426
Pomona, CA 91769

Nickus, Gary
Sales Engineer
FLW
31162 San Clemente
Hayward, CA 94544
415-487-2222

Niedrauer, Jerome J.
Manager, Metrology Engineering
Lockheed Missiles & Space Co., Inc.
P. O. Box 504
Dept. 48-72, Bldg. 182
Sunnyvale, CA 94086
408-742-5180

Noe, Larry R.
Supervisor, Mech. Sec.
NARF Alameda
Navy Stds. Lab., Code 662
Prouction Engineering, Code 660
Alameda, CA 94501
415-869-3137

Norton, Gaylen
Tech. IV, Calibration Lab.
EG & G, Inc.
130 Robin Hill Rd.
Goleta, CA 93117
805-967-0456

O'Brien, Tom
Manager
Argo Systems
885 Hermosa Ct.
Sunnyvale, CA 95408
408-737-2000

O'Halloran, Francis
O'Halloran Associates
1020 Corporation Way
Palo Alto, CA 94303
415-326-1493

Parson, Kenneth N.
Head, Met. Management Div.
Strategic Weapons Facility Pacific
SPB, TSB
SPB 23/TSB
Bremerton, WA 98315
206-396-4535 or 396-4536

Paul, Phillip H.
Res. Asst. Mech. Eng.
Stanford University
Dept. of Mech. Engr.
Stanford, CA 94305
415-497-1823

Peeler, Charles
Supervisor, Elec. Engr.
NARF Alameda
2513 Olive Ave.
Fremont, CA 94539
415-869-3137

Perry, Robert
Director of QA
Chamberlain
P. O. Box 1809
Nogales, AZ 85621
1-602-281-0931

Pervere, Michael
Marketing Eng./Marketing
Hewlett-Packard Co.
1400 Fountain Grove Parkway
Santa Rosa, CA 95401
707-525-1400

Phillips, Paul G.
Technical Services Mgr.
Thomas & Betts
920 Route 202
Raritan, NJ 08869
201-469-4000

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Pitcock, Bob
Standards Lab. Tech.
Hewlett-Packard
5301 Stevens Creek Blvd.
Santa Clara, CA 95050
408-246-4300, X2380

Pollestad, Alf
Sr. Lab. Sp.
I.B.M.
5600 Cattle Rd.
Dept. 358/001
San Jose, CA 95193
408-256-2651

Pryshepa, John
Bruel & Kjaer
881 Sneath Ln.
San Bruno, CA 94066
415-574-8100

Puening, Doug
Mgr., Mfg. Engr.
Genrad
2855 Bowers
Santa Clara, CA 95120
408-727-4400

Quart, Irving
Sr. Scientist
Hughes Aircraft Co.
P. 0. Box 902
Reliability Dept.
El Segundo, CA 90245
213-616-6647

Quinn, Carl
Vice President
Simco
382 Martin Ave.
Santa Clara, CA 95050
408-727-3611

Quinn, Joann
Guest Proaram Director
2299 Valerie Court
Campbell, CA 95008
408-374-2957

Raisanen, W. R.
President
Compu-trac, Inc.
2078 E. University Drive
Tempe, AZ 85281
602-894-2732

Ramirez, Ron
V.P. Marketing
Weinschel Engineering
One Weinschel Lane
Gaithersburg, MD 20760
301-948-3434

Reyes, Roberto P.
Engineer/Metrology
Litton Guidance & Control
13103 E. Golondrina St.
Moorpark, CA 93021
213-715-3217

Ric'kman, Robert
Sr. Inst. Eng.-Western Engrg.
Stauffer Chemical Co.
1391 S. 49th St.
Richmond, CA 94806
415-231-1262

Riley, Neil R.
Mechanical Engineering
Lawrence Livermore National Lab.
P. 0. Box 5508, L-474
Livermore, CA 94550
415-422-5888

Ringard, Richard
Owner/Mgr.
Ringard Metrology
5644 Kearny Mesa Rd., Suite L
San Diego, CA 92111
619-277-5515

Roberts, Evan J.
Manufacturing Systems Engineer
Lockheed Shipbuilding
2929 16th Ave. S.W.
Industrial Systems Department
Seattle, WA 98134
206-292-5854

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Rose, Bob
Section Manager
Litton G/CS
5500 Canoga Ave.
Woodland Hills, CA 91364
213-715-2594

Rosen, Paul
Instrulab, Inc.
P. O. Box 16
Berkeley, CA 94701
415-526-8286

Rosenthal, David
Newport Corp.
18235 Mt. Baldy Cir.
Fountain Valley, CA 90746

Rubenstein, Victor
Sales Eng.
John Fluke Co., Inc.
2300 Walsh Ave.
Santa Clara, CA 95051
408-727-0513

Rush, Dale
Supervisor, Metrology
Ford Aerospace
Ford Road
Newport Beach, CA 92660
714-720-4822

Safholm, Rick
Standards Lab. Tech.
Hewlett-Packard
5301 Stevens Creek Blvd.
Santa Clara, CA 95050
408-246-4300, X2380

Samuels, Albert H.
Sr. Staff Eng./Reliability
Hughes Aircraft Co.
P. O. Box 902
Bldg. E-l, MS Al85
El Segundo, CA 90245
213-616-6839

Sanders, Aaron A.
Physicist
National Bureau of Standards
325 Broadway
Boulder, CO 80303
303-497-5341

Schillinger, W.
Manager
I.B.M.
5600 Cottle Rd., MS K22-280
San Jose, CA 95193

Schmall, Michael
Lab. Supervisor
Simco
382 Martin Ave.
Santa Clara, CA 95050
408-727-3611

Schmidt, Lyle
Electrical Standards
U.S. Air Force
AGMC/MLEA Newark AFS
Newark, OH 43055
614-522-7683

Schultz, Richard A.
Physicist
Naval Weapons Sta.
Code 5303 I, P. O. Box 2436
Seal Beach, Pomona Annex
Pomona, CA 91769
714-620-0514

Schulz, John C.
Manager, Quality Assur. Serv.
Ford Aerospace
Ford Rd. Box A
Newport Beach, CA 92660
714-720-4787

Schumacher, Leonard
Supervisor, Instrument Service
Farinon Electric
1691 Bayport Ave.
San Carlos, CA 94070
415-594-3610

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Schumacher, Rolf
Sr. Metrologist
Rockwell International
HC02 3370 Miraloma Ave.
Anaheim, CA 92803
714-632-5981

Seal, Wendell
Manager, Metrology Engineering
TRW Elect. & Defense
One Space Park S-2470
Redondo Beach, CA 90278
213-535-5755

Serby, Bob
Division Manager
Metermaster
3995 E. Bayshore Rd.
Palo Alto, CA 94303
415-968-0313

Sevean, Frank
Eng. Sect. Supervisor
Rt. 46
Bendix Test Systems Div.
Teterboro, NJ 07608
201-393-2648

Seymore, Ken
Elec. Eng./Eng. Development
U.S. Navy Metrology Eng. Ctr.
P. 0. Box 2436
Pomona, CA 91769
714-620-0556

Sharp, De Wayne B.
Senior Engineer
I.B.M.
1550 The Alameda, Suite 301
San Jose, CA 95126
408-256-3656

Shelton, M. H.
Metrology Directorate
U.S. Army TMDE Support Grp.
DRXTM-SM
Redstone Arsl., AL 35898
205-876-1550

Shelton, Russell
Prod. Mgr.-Measuring Machines
E. Leitz, Inc.
24 Link Drive
Rockleign, NJ 07647
201-767-1100

Shurts, J. A.
QC Eng.
Exxon Nuclear Co., Inc.
2101 Horn Rapids Rd.
Richland, WA 99352
509-375-8100

Sieg, Fred H.
Quality Assurance Manager
Simco
382 Martin Ave.
Santa Clara, CA 95050
408-727-3611

Siegel, Samuel
Vice President
Volumetrics
634 Airport Rd.
Paso Robles, CA 93446
805-239-0110

Simmons, Bill
Manager, Metrology
Barrius Technology, Inc.
1607 Wavecrest Ln.
Houston, TX 77058
713-480-1889

Simmons, Joe D.
Deputy Director
National Bureau of Standards
Center for Abs. Phys. Quantities
Washington, DC 20234
301-921-2001

Smalley, W.
Engineer
DALFI
10080 Carroll Canyon Rd.
San Diego, CA 92131

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Smith, Dan
Sales Manager
Maury Microwave
8610 Helms Ave.
Cucamonga, CA 91730
714-987-4715

Smith, Gary L.
Training Manager
Metron Corp.
9681 Business Center Dr.
Ran. Cucamonga, CA 91730
714-980-6166

Smith, Janice
Mgr., Sales Admin.
Simco
382 Martin
Santa Clara, CA 95050
408-727-3611

Smith, Mark
Electrical Engineer
Hart Scientific
54 North 400 West
Provo, UT 84603
801-375-7221

Stanley, George C.
Training Mgr., Interface Sys.
Hewlett-Packard
1819 Page Mill Rd.
Palo Alto, CA 94304

Stark, Larry
Appl. Engr.
Hewlett-Packard
1501 Page Mill Rd.
Palo Alto, CA 94304
415-857-1501

Stern, Naftali
Calib. Dept. Manager
Government of Israel
P. 0. Box 2250
Haifa, Israel

Stockwell, Bob
Instructor, Instr. Train.
Hewlett-Packard
1819 Page Mill Road
Palo Alto, CA 94304
415-857-4253

Stoehr, Fred G.
Engineer/D327
I.B.M.
3605 NW Highway 52
Rochester, MN 55901
507-286-5192

Stone, Jay
President
Jay Stone & Assoc.
339 s. San Antonio Rd.
Los Altos, CA 94022
415-948-4563

Stratton, Jim
Branch Manager
Esterline-Angus
563 E. Lewelling Blvd.
San Lorenzo, CA 94580
415-278-4502

Streeter, Maxwell
Quality Assur. Dept.
Pugent Sound Naval Shipyard
Bremerton, WA 98314
206-476-3111

Taff, Hillary A.
Chief, Central Lab. Serv.
Tennessee Valley Authority
LA PSC 1
Chattanooga, TN 37401
615-697-4317

Taylor, Jack
Reg. Mgr.
U.S. Inst. Rental
511 W. Golf
Arlington Hts., IL 60005
312-931-1600

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Thompson, Roger
Calibration Supervisor
Ampex Corp.
600 Wooten Rd.
Colo. Springs, CO 80915
303-570-3265

Thurbon, Jr., John E.
Supvry. Eng. Tech.
Naval Weapons Station
Code 063
Navy Stds. Lab.
Seal Beach, CA 90740
213-594-7224 or 7544

Trinite, George M.
Branch Head
Metrology Engineering Center
P. 0. Box 2436
Pomona, CA 91769
714-620-0552

VanGroos, John
General Manager
True Time Instruments
3243 Santa Rosa Ave.
Santa Rosa, CA 95401
707-528-1230

VanWinkle, Charles
System Analyst
DALFI, Inc.
10080 Carroll Canyon Rd.
San Diego, CA 92131
619-578-9500

Varvel, Jay R.
Metrologist, QA Prog. Devel.
Rockwell Hanford Operations
P. 0. Box 800, 2101M/200 East
Richland, WA 99352
509-373-1907

Vavken, Roland
Manager, Metrology Operations
Rockwell International
3370 Miraloma Ave.
Dept. 120 031-HC02
Anaheim, CA 92803
714-632-3560

Vega, Henry A.
Mech. Engineer
Navy Metrology Eng. Ctr.
P. 0. Box 2436
Pomona, CA 91769
714-620-0565

Vorne, Richard A.
Mgr., Metrology Support Serv.
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Orgn. 48-73, Bldg. 151
Sunnyvale, CA 94086
408-743-2040

Wagner, Rick C.
Metrology Engineer
McDonnell Douglas Astronautics Co.
5301 Bolsa Ave.
Huntington Bch., CA 92646
714-896-3028

Walczak, K. M.
Scientist, R&D Services
Owens-Corning Fiberglas
Technical Center
Granville, OH 43023
614-587-8049

Walker, David
Sales Manager
DATRON
209 Loyola Rd.
Costa Mesa, CA 92626
714-545-8115

Warwick, Ed
Sr. Metrologist Spec.
I.B.M.
5600 Cottle Rd.
Dept. 358/001
San Jose, CA 95193
408-256-2644

Weatherstone, Joe
Manager
Bruel & Kjaer
1542 E. Katella
Anaheim, CA 94152
415-574-8100

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Weber, Charles
Engineering Supervisor
Grumman Aerospace
MS A07/12
Bethpaqe, NY 11714
516-575-3281

Weber, Robert L.
Manager, Metrology
Lockheed Missiles & Space Co., Inc.
P. 0. Box 504
Orqn. 48-70, Bldg. 151
Sunnyvale, CA 94096
408-742-2957

Weir, John T.
Y-Program
Lawrence Liver-more National Lab.
P. 0. Box 5508, L-482
Livermore, *Ch 94550*
415-422-5986

Werner, H. Bryan
Head of Standards Lab.
Westinghouse Electric Corp.
1310 Beulah Rd.
Research & Development
Pittsburgh, PA 15235
412-256-3420

Westover, Keith
Mgr. Calibration, Metrology
Intersil, Inc.
10710 North Tantau Ave.
Cupertino, CA 95014
408-996-5671

Whittier, Robert M.
Mgr., Development Engineering
Endevco
30700 Rancho Viejo Rd.
San Juan Cap., CA 92675
714-493-8181, X302

Wibbenmeyer, Ken W.
Unit Chf., MCAIR Bur. of Stds.
McDonnell Douglas Corporation
P. 0. Box 516
Dept. 257, Bldg. 102
St. Louis, MO 63166
314-234-1817

Willett, Bob
Tech. Staff Member/Mfg. Enq.
Rockwell International
1200 North Alma Rd.
Collins Radio Division
Richardson, TX 75081
214-996-7051

Wilson, Warren L.
Engr., Metrology
Fairchild Test Systems
1725 Technology Dr.
San Jose, CA 95115
408-998-0123

Wingfield, Alfred
Elect. Meas. Equip. Mech. Ldr.
Commanding General (B183)
Marine Corps Logistics Base
Attn: Civilian Personnel Office
Barstow, CA 92311
619-577-6486

Wood, Dan
Quality Engineer
American Heyer-Schulte
600 Pine Ave.
Goleta, CA 93117
805-653-7354

Woodbridge, Keith
Quality Engineer
Eastman Kodak
901 Elmgrove Rd.
Dept. 5, Bldg. 6
Rochester, NY 14650
716-726-4475

Worrell, Ralph
Sales Coordinator
Marotta Scientific Controls, Inc.
17671 Irvine Blvd., Suite 202
Tustin, CA 92680
714-544-2160

Yamashita, Judith
MTS
TRW
One Space Park
Redondo Beach, CA 90278
213-535-2445

MEASUREMENT SCIENCE CONFERENCE ATTENDEES

Yeap, Arthur K.
Bruel & Kjaer
881 Sneath Ln.
San Bruno, CA 94066

Zack, A. T.
Engr.. T&M
GTE Products Inc.
100 Endicott St.
Danvers, MA 01923
617-777-1900

Zall, Harvey Michael
Site Manager
Simco/NASA Ames
382 Martin Ave.
Santa Clara, CA 95050
415-965-5465

1983 MEASUREMENT SCIENCE CONFERENCE "MEMORIES"

"STONEFACED" CONFERENCE DIRECTOR, ROLAND VAVKEN, LEADS THE 1983 MSC TO SUCCESS WITH HIS DYNAMIC OPENING SPEECH.

SOME OF THE CONFERENCE LEADERS: (FROM LEFT TO RIGHT) CONFERENCE DIRECTOR, ROLAND VAVKEN; CHAIRMAN OF THE BOARD, BILL STRNAD; PUBLICITY CHAIRMAN, BILL BROWNE; AWARDS CHAIRMAN, JOHN BRADY, TREASURER, DAVE BUCK, ARRANGEMENTS, CHET CRANE.

MORE CHAIRMEN AND GUESTS: PUBLICATIONS, JOHN SCHULZ; PROGRAM, BOB MONROE; MRS. GLEN ENGEN; WOODINGTON AWARD RECIPIENT, DR. GLEN ENGEN, SPEAKERS CHAIRMEN, FRANK KOIDE; PRESIDENT OF IEEE, DR. ROBERT LARSON.

AN NCSL HAPPENING AT THE 1983 MEASUREMENT SCIENCE CONFERENCE

SEVEN NCSL PAST PRESIDENTS HONORED THE MSC WITH THEIR PRESENCE, FROM LEFT TO RIGHT, JERRY HAYES, DEAN BRUNGART, MIKE SUEACCI, DON GREB, DAVE MITCHELL, JOHN MINCK, AND JOHN LEE.

THURSDAY LUNCHEON SPEAKER
DR. ROBERT LARSON, PRESIDENT
OF IEEE AND PRESIDENT, SYSTEMS
CONTROL CORPORATION.

MSC'S CHAIRMAN OF THE BOARD,
BILL STRNAD, NEVER LOST FOR
WORDS . . . WELL MAYBE JUST THIS TIME!

OUR ATTENDEES AT THE OPENING SESSION — 1983 MSC

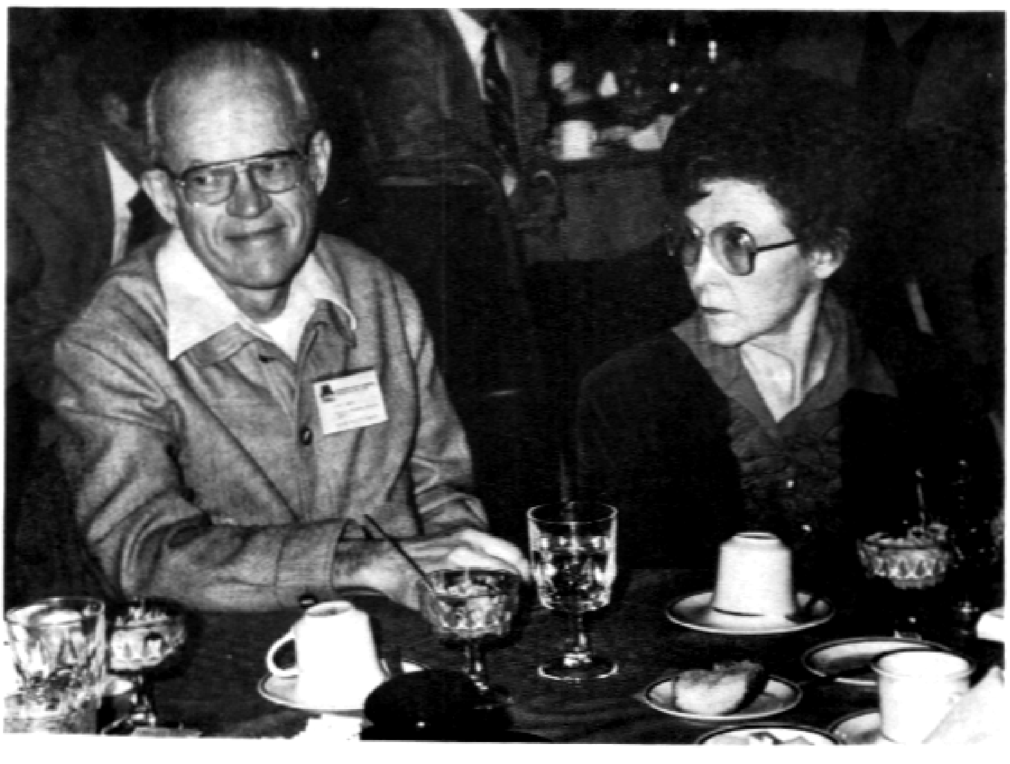
DR. LARSON RECEIVES A CERTIFICATE OF APPRECIATION
FROM DIRECTOR, ROLAND VAVKEN

DR. JOEL S. BIRNBAUM, FRIDAY LUNCHEON SPEAKER,
RECEIVES A CERTIFICATE OF APPRECIATION FROM DIRECTOR,
ROLAND VAVKEN.

WOODINGTON AWARD RECIPIENT

DR. GLENN ENGEN

"FOR PROFESSIONALISM IN METROLOGY"

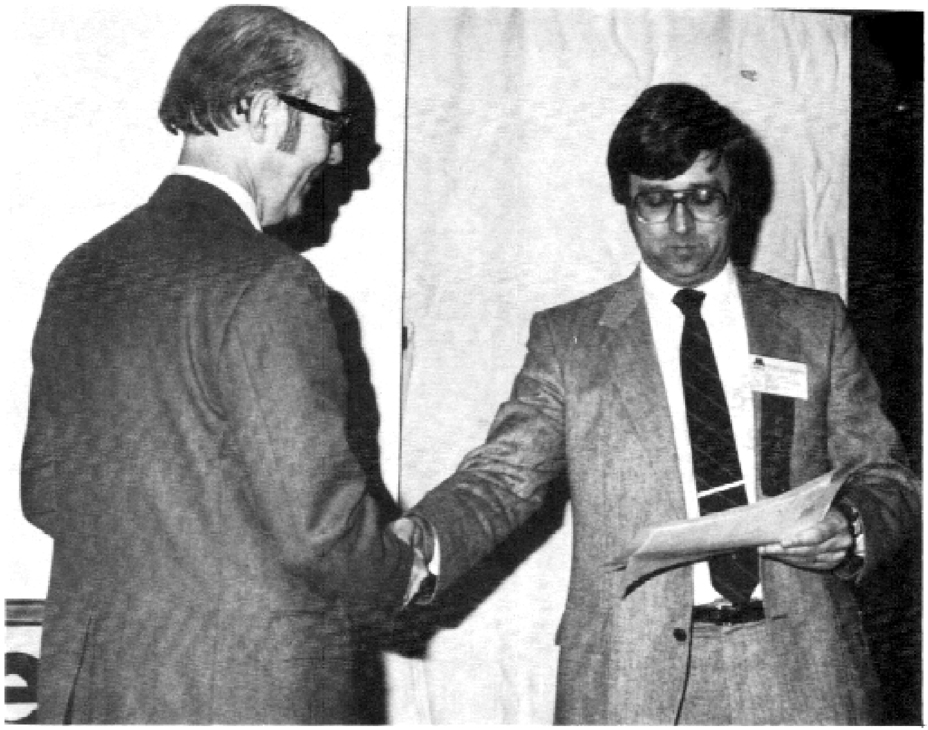


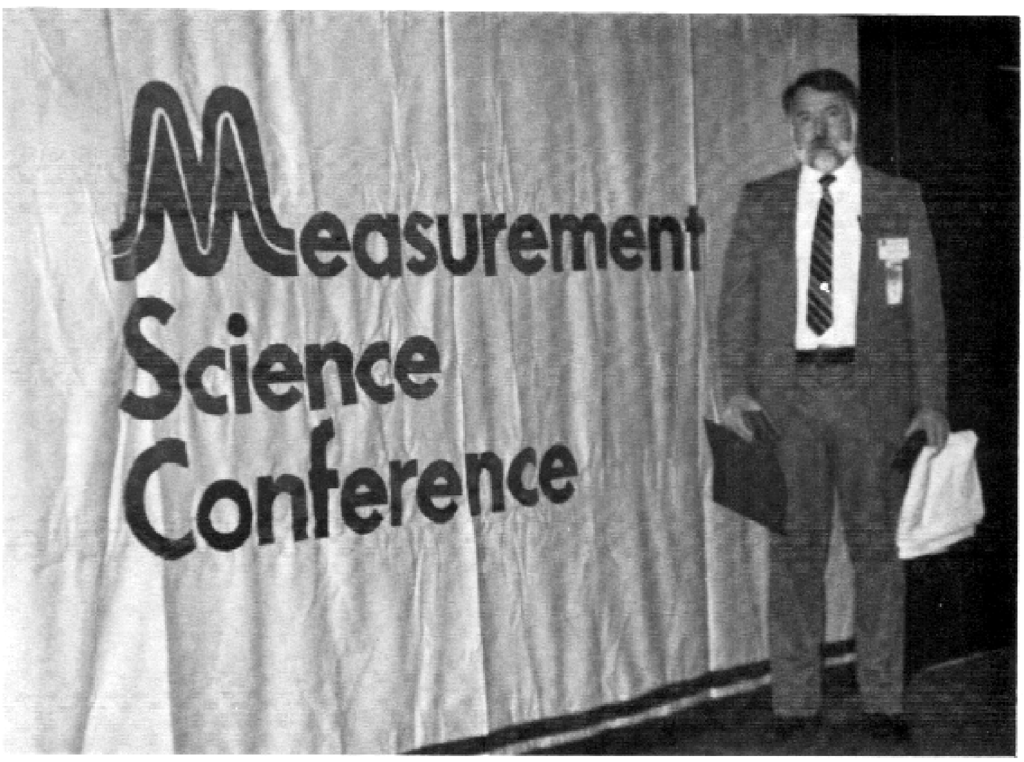
DR. ENGEN AND HIS WIFE, SADIE

OUR SPEAKERS IN ACTION

DR. JOEL BIRNBAUM TELLS US HOW COMPUTERS WILL INTERACT WITH INSTRUMENTATION IN THE FUTURE.

SESSION DEVELOPER, DR. BRIAN BELANGER THANKS FELLOW NBS'er CHUCK MILLER FOR PARTICIPATION IN BRIANS SESSION.





"WHAT DO WE DO NOW?"

EXHIBITS


Valhalla Scientific Inc.
Valhalla Scientific Inc.
Valhalla Scientific Inc.

A WORKSHOP ON SMART INSTRUMENTS

WINE TASTING FOR ALL – (LEFT TO RIGHT) KEYNOTE SPEAKER DAVE MITCHELL; SPEAKER, ROLF SCHUMACHER WITH WIFE, MARLENE; DOOR PRIZE CHAIRMAN, BOB COUTURE WITH WIFE, JOAN.

"DON'T RUSH ME!" SAYS DOOR PRIZE CHAIRMAN COUTURE

"LET'S TAKE THIS ONE HOME WITH US!"

"I WANT THIS ONE!"

"THE FINAL PAYOFF!"
ALGIE LANCE WINS A CASH DOOR PRIZE; BOB MONROE VERIFIES IT.