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SPECIAL REPORT

TECHNICAL/APPLICATIONS SECTION

DEPARTMENTS

ON THE COVER: Two new network analyzers, a Marconi scalar system and a Flann vector system, reflect a strong effort by English instrument suppliers to participate in the growing automatic test equipment market. Articles describing the systems begin on pages 83 and 89, respectively.

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A History of Automatic Microwave Network Analyzers

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Introduction

To keep this report within manageable boundaries, it will be limited to network analyzer systems that have either been offered commercially and/or manufactured in significant numbers (more than 20) since 1960 in the U.S.. This will not credit a large number of early researchers and one-of-a-kind systems, but all those from Nyquist of Bell Labs in 1930 through 1976 have already been very effectively catalogued in Bob Beatty's NBS Monograph 151-"Automatic Measurement of Network Parameters—A Survey".

Also, except for a few introductory remarks about the first commercial manual vector network analyzersof the mid 60's, the survey will focus on computer controlled systems.

The First Manual Vector Instruments

The first microwave vector network analyzers were available commercially from Rantec of Calabasas, CA. Based on the work Cohn, Oltman and Weinhouse[1] in the early 60's, these systems employed a balanced modulator to amplitude modulate a microwave source. These systems were dependent upon components like waveguide E-H tees and couplers to develop 90° phase differences. Due to the narrowband nature of these components, the Rantec ET210 systems (Figure 1) as well as others developed in the mid 60's by Peter Lacy of Wiltron (Mt. View, CA), and Andrew Alford of Alford (Winchester, MA) (Figure

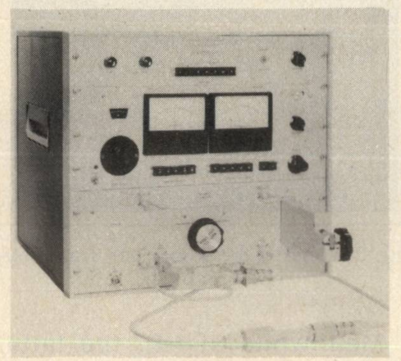

Fig. 1 Rantec Model ET210CX multifunction test system (network analyzer).

2), were available only as octave-wide instruments.

Meanwhile at HP, the first broadband instrument capable of measuring phase from 1 MHz to 1 GHz (HP8405A) was introduced in 1965[2]. It utilized a sampling type harmonic mixing scheme which phase locked a harmonic of a low frequency VCO to the reference channel high frequency signal.

This led to the announcement two years later[3] of the HP 8410A, MHz to 12.4 GHz without changing components in the receiver. The microwave sources of that era were dependent on BWO tubes of octave bandwidth, necessitating source switching for multi-octave operation above 2 GHz. Full utilization of the broadband swept receiver capability at microwave frequencies had to wait until the multi-octave solid-state (Figure 3) a broadband network analyzer capable of measuring reflection and transmission coefficients on a swept basis from 110 sources of the mid 70's. Nonetheless, there was considerable economic appeal in a microwave network analyzer capable of 7 octave operation for about the cost of the other single octave manual instruments.

Before we proceed with the computer-based systems, we should single out the efforts of Dan Leed at Bell Labs, Holmdel,

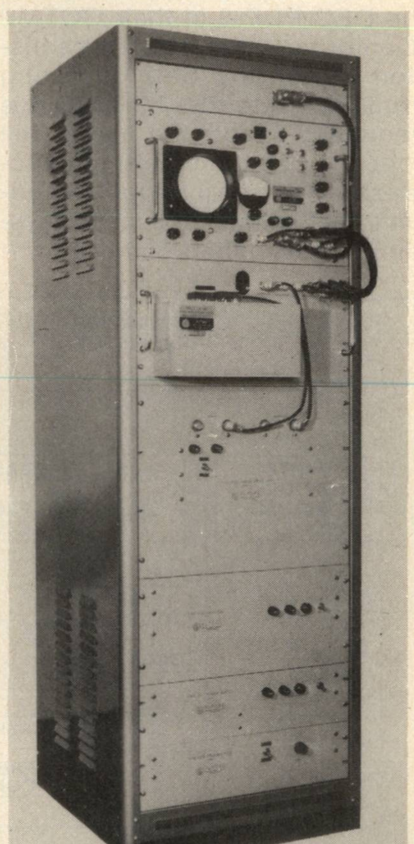

Fig. 2 Alford Automatic Plotter — for measurement of phase shift, attenuation and impedance.

NJ in the early 60's. His work with a manual 250 MHz network analyzer was followed by the development of a 4.2 GHz system to characterize transistors. This work[4], published in 1965, was the first vector measuring system that used the concept of an "error model" and a computer for accuracy enhancement. He abandoned efforts to make a "perfect" measuring jig or fixture at 4.2 GHz and instead pre-characterized the errors due to the fixture using a series of known devices. He fed this characterization, as well as the uncorrected data on the transistors, into a separate large standalone computer for error correction.

The First Computerized Network Analyzers at Bell Labs and HP

This concept of error modeling was expanded both at Bell Labs and Hewlett Packard, in the 1966-1968 time frame, to include the computer as an integral part of the measuring system.

The Bell System approach used the DEC PDP-8 in their COTMS (Computer-Operated Transmission Measuring Set) operating from 50 Hz to 250 MHz. In this frequency range, the major Bell concern was the precise characterization of transmission components. In their communication systems large numbers of these components were operated in cascade making extremely small distortions (like .001 dB and .01° variations versus frequency) significant. Key to achieving this ultra-high resolution was the utilization of "microbelling". (Figure 4) To eliminate effects of measuring system drift, a stable standard was compared on a continuous basis. Other key contributors to COTMS were Evans, Geldart, Haynie, Hempstead, and Rosenfeld.

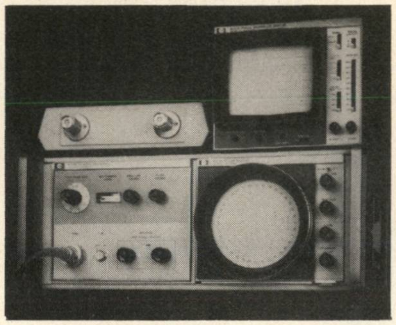

Fig. 3 The HP 8410 receiver - an ANA building block.

Meanwhile at HP, the latter stages of the development of the 8410A network analyzer[5] in 1966-67 was coincident with the introduction of Hewlett Packard's first mini-computer—the 2116A.

The concept of real-time computer error-correction was employed in the first commercial automatic network analyzer—the HP 8540A—sold to Microwave Associates in 1967. In its frequency range (up to 12.4 GHz) the requirement for computer accuracy enhancement was very clear. Broadband couplers were capable of only 25 dB directivity. Mismatch error effects associated with 20 dB source and load matches caused errors of 1 dB or more when characterizing high reflection devices like transistors.

Then as now, the desire for equivalent directivity of 45dB or more and transmission accuracies of 0.1 dB and 1° measuring at the 0-20 dB insertion loss/gain level was a very strong motivation to adopt computer error correction techniques. Rapid acceptance by the microwave industry led HP to continue development of the microwave ANA. Early systems were built on a custom order basis, briefly designated HP 8541A, as the system evolved from reed relay programmed BWO sources using BCD voltmeters as A-D converters. The HP system designation stabilized as Model 8542A for a period of four years from 1969-73. Key contributors to this evolution of the HP 8540A up to the 8542A were Hackborn, Ray, Adam and Bodway. During this time, the HP minicomputer used went from HP 2116A to 2115A to 2116B to 2114A. Likewise, the option of phase-locking the microwave source to a harmonic of a VHF synthesizer (HP 5105A) allowed the system both excellent frequency accuracy and freedom from a random measurement error known as harmonic skip. This error results when different harmonics of the receiver VCO are chosen by the phase lock loop between calibration and measurement. Because the local oscillator power level applied to the sampling mixer varies between the time when the reference is stored and later measurements, non-repeatabilities of up to 0.2 dB can be observed.

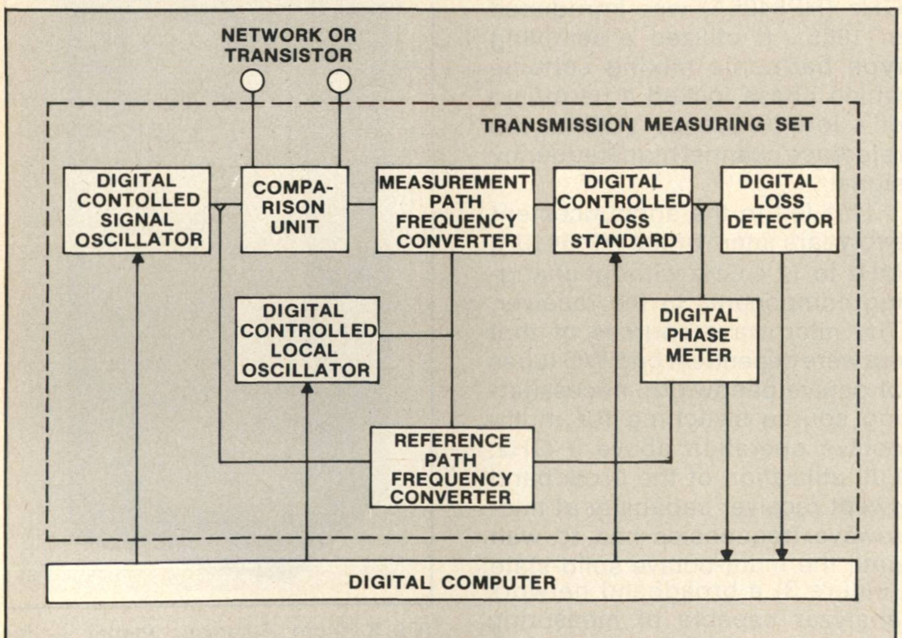

Fig. 4 Block diagram of the first BTL COTMS.

ANA's of the Early 70's

Another HP automatic system, designated the 8543A, was configured around the HP 8407A 100 kHz-110 MHz network analyzer. This system attempted to achieve the accuracies of COTMS using

[Continued on page 46]

microbel techniques. It came within a factor of two of COTMS performance at considerably less cost but was nowhere near the commercial success of the HP 8542 series systems.

In 1972, the author rejoined HP and incorporated software originally conceived at Computer-Metrics in a new variation of the HP microwave ANA—the 8542B. This software was developed over several years of operating 8542A's as microwave measurement service bureaus with the efforts of Cote, Rosenzweig, and Uhlir.

The 8542B, (Figure 5) the most popular of HP's minicomputer based ANAs, was built around a HP 8500A graphics display system employing the HP 2100A computer. The measuring hardware was also updated with a new precision detector. Key contributors were Rytand, Showman and Neering.

Also in 1973, HP introduced another microwave ANA—the HP 8545A—based on the early solid-state swept sources and employing a time-shared computer system over phone lines. During this time frame, Wiltron also offered a time-share approach. Both were commercially unsuccessful.

Early in 1974, automatic system activities grew out of the Stanford Park site of HP. Production responsibility was transferred to the Automatic Measurements Division in Sunnyvale with much of the R & D activity shifting to Santa Rosa. From that point, the HP 8542B evolved to the 8542C as a hard disk based system selling for close to $300K.

Meanwhile, in the early 70's, Bell Labs had expanded COTMS to cover 50 Hz-1 GHz as well as developing translators (appliques) to cover 1-4 GHz and 3.7-12.4 GHz. About 20 of these systems were manufactured at WECO, Kansas City. Also, design activity led by Dan Leed was focused on a newer ANA system designated MINI-COTMS. While it never achieved the goal of lower cost, it did accomplish its primary goal of higher speed. Operating from 200 Hz to 500 MHz, it can display 400 error-corrected points/second using a DEC PDP-11/34. It featured 75Ω operation and several specialized appliques, including a non-linear system for intermodulation testing. Twenty-three of the MINI-COTMS were manufactured in Kansas City. The psuedo real time error correction has made the system a workhorse in the manufacture and adjustment of filters. Bell Labs design activity in ANA's has been dormant since the mid 70's, largely due to their concentration on digital communication systems.

In 1973, Gorss of General Radio[6] introduced the model 1710 RF network analyzer operating from

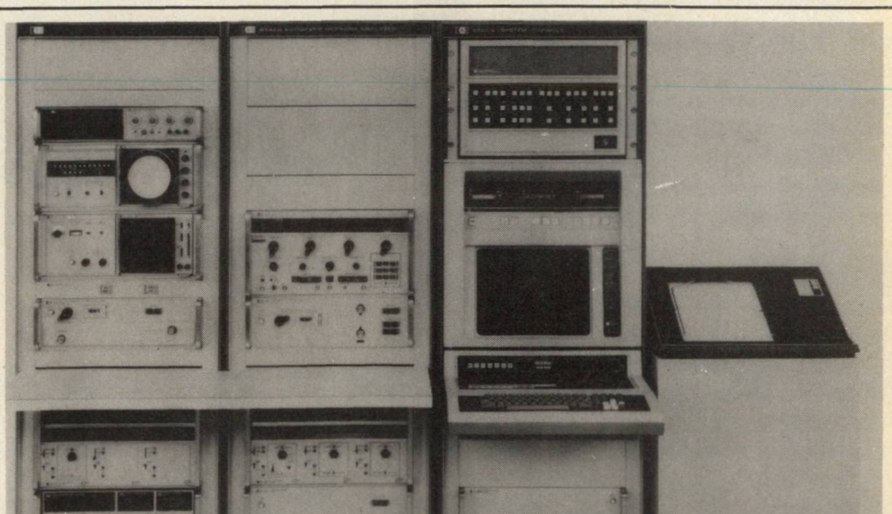

Fig. 5 The HP 8542B mini-computer based ANA.

[Continued on page 48]

[From page 46]

.4 to 500 MHz and its computer controlled version—the GR2260 For several years, this system was the "state of the art" commercial system in this frequency range.

The first HP network analyzer designed from conception as a computer-compatible system was introduced[7] from Santa Rosa in 1976. The HP 8505A (Figure 6) covering 0.5-1200 MHz, rapidly became the "new state of the art". It featured HP-IB which is HP's implementation of the IEEE-488 eight bit parallel-byte serial interface system that has become the world standard for instruments. This highly popular instrument has been offered with a variety of desktop computers as factory configured automatic measurement systems designated the HP 8507 (A with HP 9830, B with HP 9825, C with HP 9845. Among the key contributors were Rytting, Vifian, Sharrit, and Barr.

The HP-IB Microwave ANA

In 1967, as more instruments and accessory instruments ("glue-boxes") became available with HP-IB, HP Santa Rosa began the applications engineering activity that culminated in Application Note 221 which described an ANA Utilizing the multi-octave HP-IB sweep oscillator, the 9825 desktop controller and our old friend, the 8410 network analyzer system, now interfaced to the computer via an HP-IB A-D converter and relay actuator. This was intended as a simpler automatic system offering less sophisticated error correction not intended to rival the accuracy of the HP 8542 system, but had significantly lower cost. The application note proved so popular that HP began offering the HP 8409A, a factory configured system for about $75K. The large improvement in price-performance, coupled with difficulties with the older, less reliable BWO-based system, led us to obsolete the HP 8542.

Based around the HP 9845 desktop controller, the HP 8409B system was upgraded to include higher accuracy calibration with 12 term error correction, a phase-locked synthesizer scheme to eliminate harmonic skip, and dual test sets with switchover capability in a rack-mounted configuration. Performance rivalled and in most cases exceeded the old HP 8542 series, with a factor of 4 better reliability and considerably more flexibility in ability to modify both hardware via the HP-IB and software using the friendlier desktop controllers. Other key contributors included Rytting, Courreges, Grace, Kachigan, Ramey and Williams.

Also in 1980, Weinschel Engineering (of Gaithersburg, MD), introduced the Model VM-4A Attenuator/Signal Generator Calibrator[8] (Figure 7). This system features 0.01-18 GHz performance in two bands with dual channel, high accuracy (.02 dB/10 dB), wide dynamic range and phase capability. The system addresses the metrology market, measuring transmission characteristics of

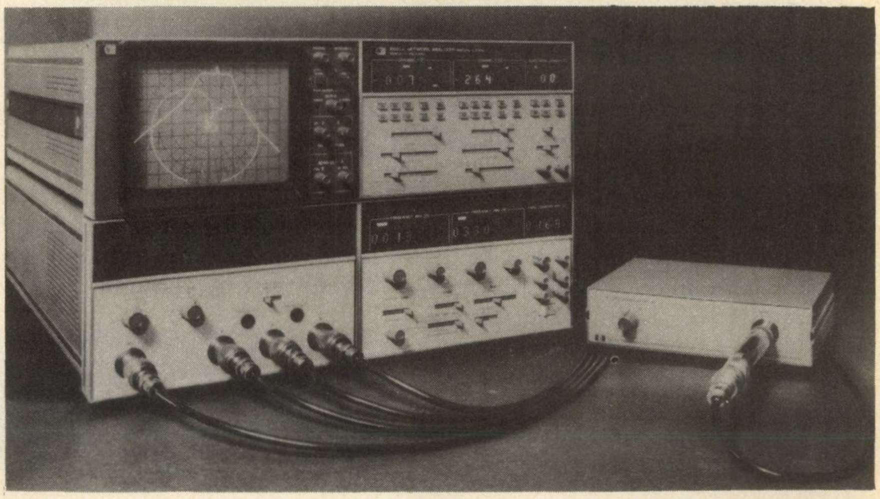

Fig. 6 The HP 8505A network analyzer.

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[From page 48] **NETWORK ANALYZERS**

attenuators and couplers. It is available with an IEEE-488 interface.

In the same time frame, several IEEE-488 based scalar network analyzers and automatic systems came on the market. While the Wiltron 5610 systems (Figure 8) do not have direct phase capability, desktop computer software is available utilizing air line ripple and Fourier techniques to provide accuracy enhancement and phase data in certain applications.

Using HP-IB accessory instruments, HP offers the HP 8755P based on its scalar network analyzer and new digital sweeper mainframe. The controller employed is the low cost HP-85.

Another scalar receiver using broadband detectors was introduced last year by Pacific Measurements of Sunnyvale, CA. The model 1038-N10 was the first scalar instrument to fully automate (program front panel controls and most calibration, frequency change and zeroing functions) via IEEE-488.

While the above three scalar systems have not generally replaced the ANA in the R&D applications, they have become

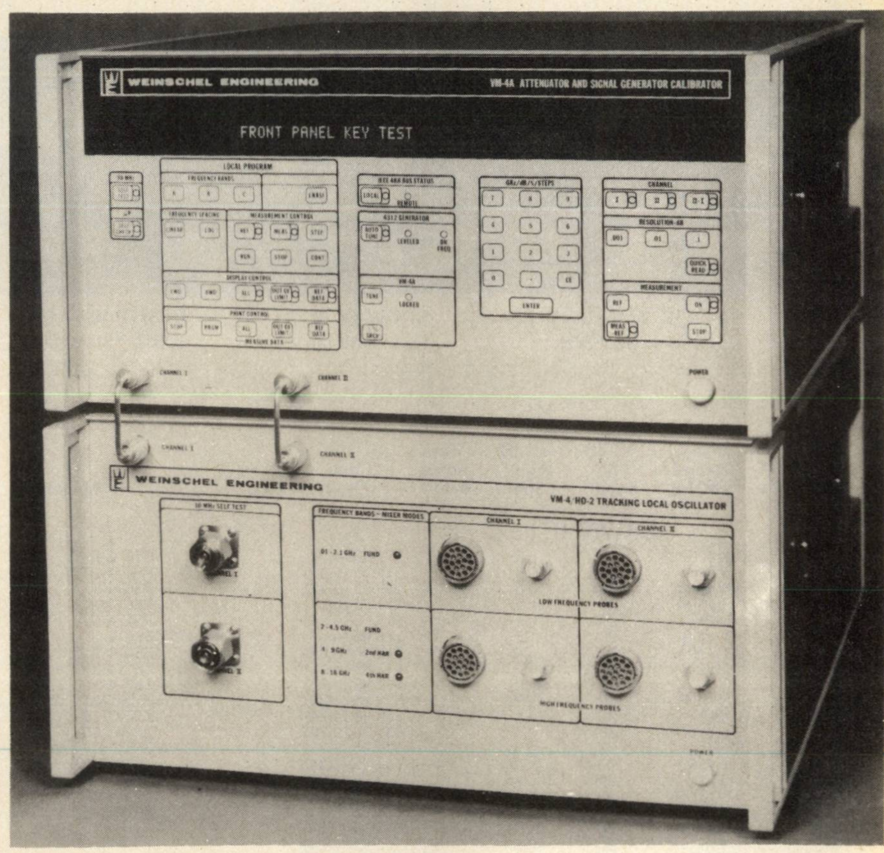

Fig. 7 Weinschel VM-4A microprocessor controlled measurement receiver.

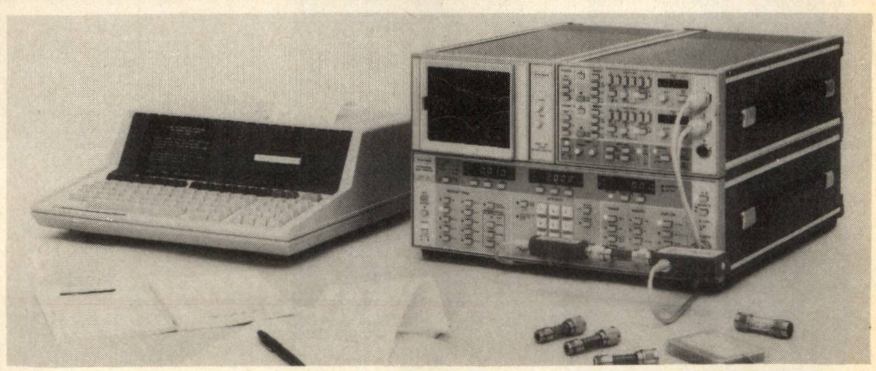

Fig. 8 Wiltron automated scalar network analyzer system.

[Continued on page 54]

popular in efforts to automate production activities.

HP's most recent offering in the ANA arena late in 1981 involves two new versions of a HP 8410 based automatic system. The top of the line offering has been updated to include the latest digital mainframe sweep oscillator—the HP 8350—as well as the latest desktop controllers. The HP 8409C (Figure 9) can be provided either with the HP 9845B Basic Series 200 or the 9826 (HPL) controller, as well as wide variety of frequency range/test set/synthesizer phase lock options. Prices range from $87K to $151K.

Also now available as a lower cost alternative is the HP 8408A (Figure 10) automatic system using the HP-85 controller (0.5-18 GHz) (for about $60K). Using a new test set manually switched between transmission and reflection, the system provides automatic capability at manual system prices. Costing only 30% more than scalar-only systems it features the 60 dB spurious free dynamic range of the HP 8410 system, along with computer error correction for

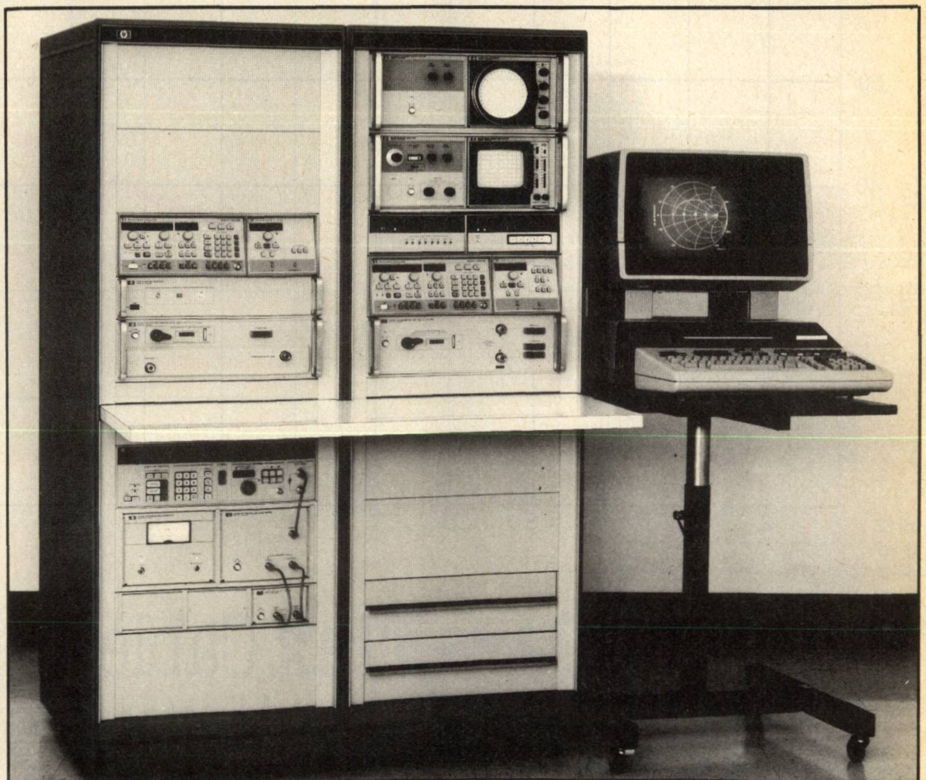

Fig. 9 The HP 8409C desktop computer based ANA.

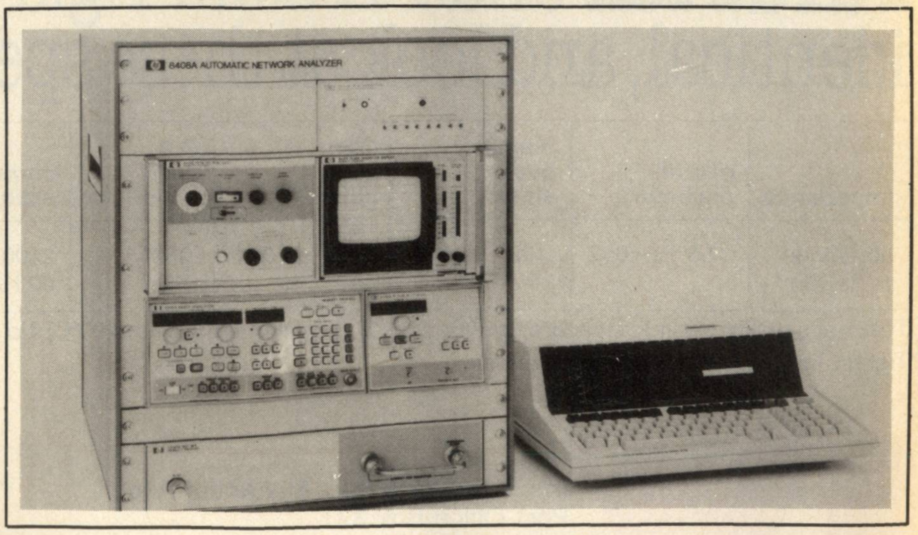

Fig. 10 The HP 8408A low cost ANA.

[Continued on page 56]

directivity and source match, and frequency response.

Other Contributors

Although we initially limited the scope to exclude the research or one-of-a-kind or pure software activities, a survey like this must at least mention the work of Engen and Hoer at NBS on six-ports, Speciale of TRW on TSD calibration, Stinehelfer & Hines on time domain, and the Europeans: Shurmer, DaSilva, McPhun, Kasa, Rehnmark, Woods and Pollard on calibration techniques. Pioneering efforts in networking of systems at M/A-COM and by Perlmann of RCA, as well as application activities too numerous to credit in fields as diverse as cancer research and antenna measurement, have made these last two decades an exciting time in this field.

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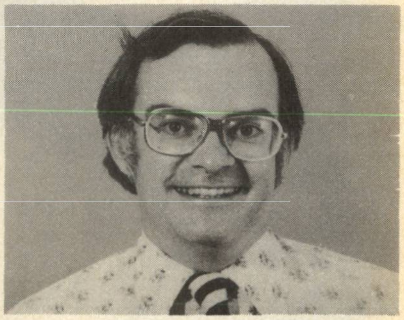

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At HP since 1972, he has been responsible for the marketing and development of the HP 8409 family of network analyzers. He was involved in software design for the HP 8507 systems and the HP 8542B.

From 1969 thru 1972 Jim was Executive Vice President and Engineering Manager of Computer-Metrics, Rochelle Park, NJ, co-founder of this microwave measurement service bureau.

From 1966 thru 1969 he was a Field Engineer/Account Manger for HP in New Jersey.

His first six years after B.E.E. in 1969 from Manhattan College were spent in microwave design at ITT Federal Laboratories in Nutley. N.J.;, Budelman Electronics in Stamford, Conn., and Western Union's Radio Research Division in New York.

Design accomplishments included the local oscillator/Beacon of INTELSAT III, the first FCC type-accepted GHz solid-state transmitter and other solid-state amplifiers, multipliers and mixers used in both ground and space communications. ■

Versatile Roles For Processed Scalar Network Analyzer Data

Dr. Peter Lacy
Wiltron Company

Introduction

The Scalar Automated Network Analyzer (SANA) has proved quite versatile in a number of microwave network measurement roles. This includes frequency domain reflection and transmission measurements, where the phasor measurement system errors are virtually eliminated; and distance to-fault measurement on transmission feed trunks and other multiple reflection configurations. The method requires step frequency scan of the distributed network under analysis and the application of digital signal processing algorithms. Thus, precision metrology, laboratory investigations and field diagnostics are encompassed. Broadband network measurements are emphasized.

Measurement System Configuration

The measurement system includes the following ingredients:

- Microprocessor based signal generator and logarithmic scalar analyzer.
- Precision RF components — reflection bridges, air-lines, etc.
- Digital Signal Processing (DSP) algorithms for computer execution.

The measurement system is controlled and the raw data is digitally processed by a desk computer operating through an IEEE-488 bus. The above elements have been discussed in a previous report[1] and in the bibliography. Accuracy analysis will be presented for the stringent reflection measurement application.

Frequency And Spatial Domain Measurements

Reflection measurements in the frequency and spatial domain are accomplished by Windowed Discrete and Fast Fourier Transforms, where as, transmission measurement requires only frequency domain presentation using the Discrete Fourier Transform (zero frequency component providing low pass filter action). The measurement configurations for each are shown in Figure 1.

Frequency Domain Analyzer

This measurement configuration uses precision air-lines to separate the errors generated externally from each of the ports of network under measurement. During frequency scan a network phasor and any external error phasor go through a full cycle of interference in a frequency interval equal to C/2L where C is the velocity of light and L is the air-line length. This frequency span is required to obtain the amplitude, however, phase information is also contained within the "ripple extraction" transform and can be used to provide complex data. The windowed discrete Fourier Tranforms are described in a previous paper [2].

Briefly, for broadband measurements, many interference cycles are seen in the raw swept frequency scalar data. Then, a Kaiser-Bessel window, 3 cycles wide, is moved across the interference histogram. The window is heavily concentrated on the middle cycle of the three. Sixty four per cent of the amplitude weight exists on this center cycle. Then, either the average value (low pass filter) or the ripple amplitude (bandpass filter and peak detector) are determined. Error averaging is used to measure low values of return loss $1 \geq |\Gamma_x| > 0.03$ and for the elimination of mismatch errors in transmission measurements.

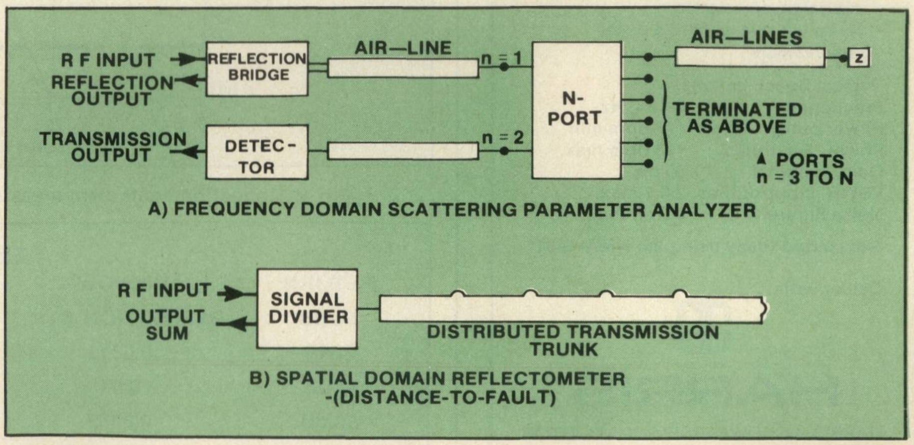

Fig. 1 Two measurement configurations for digital signal processing.

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Uncertainty Analysis In Reflection Measurement

The reflection measurement uncertainty will be discussed by reference to the bilinear transformation equation that maps Γ_x, the unknown, on the Γ_m plane introducing the measurement system errors. This is shown in Equation 1:

$$\Gamma_m = \frac{A\Gamma_x + B}{C\Gamma_x - 1} \qquad (1)$$

where A is a frequency and amplitude tracking term and through a calibration procedure, its average value is unity. B is the directivity of the reflection sensor (bridge, coupler or hybrid). Finally, -C is test port match Γ_m of the reflection sensor.

For the high performance reflection bridge, A is removed in the calibration or normalization step, further, by using successively short/open calibrations the effects of C are removed from the amplitude normalization. However, C will appear as an uncertainty in the measurement step itself. B, the directivity does not appear significantly during calibration but will predominate for the measurement of small values of Γ_x.

The log-plot of uncertainty versus diminishing Γ_x, shown as Figure 2, allows a wide range of parameters to be portrayed with straight line error contributions. The uncertainty chart illustrates $|B_b| = 0.01$ and $|C_b| = 0.1$ for the high performance reflection bridge.

Next, considering the measurement of $1 \geq |\Gamma_x| > 0.03$ corresponding to return loss values of 0 to 30 dB by means of the error averaging method that uses the low-pass digital filter. The effect of B_b and C_b are virtually eliminated, but the logarithmic response A_a dominates at low RL and the dimensional accuracy B_a at the high end of the above RL range. The instrumental stability is shown at 0.002 (±0.02 dB). For higher values of RL, the input amplifier noise labelled B_a will appear. It is shown as being unity at 50 dB RL at -55 dBm level but then having a +2 slope on the log plot due to the square law characteristic of the diode detector.

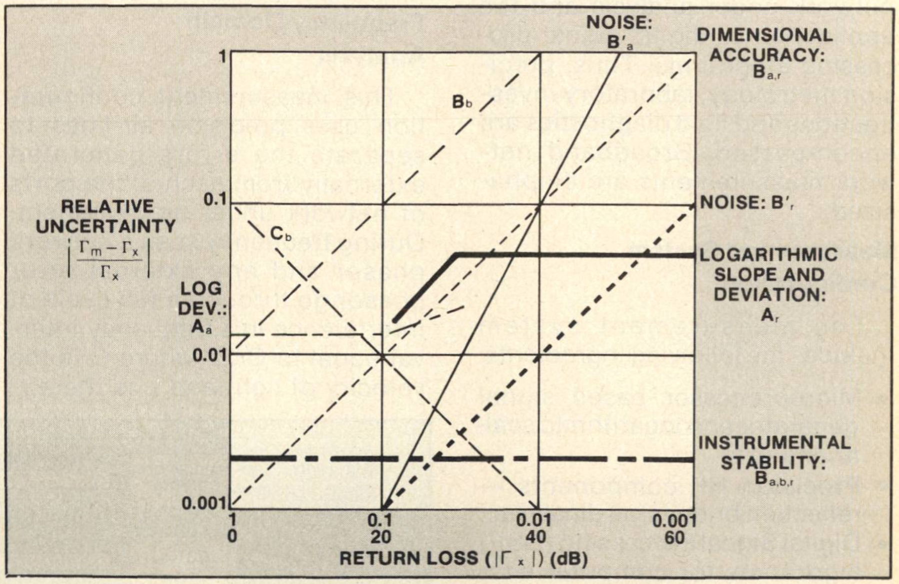


Fig. 2 Reflection coefficient measurement uncertainty factors for SANA.

TABLE 1

RETURN LOSS	UNKNOWN REFLECTION $\vert\Gamma_x\vert$	UNCERTAINTY $\vert\Delta\Gamma_m\vert$	SIGNAL/ NOISE RATIO
30dB	0.0316	0.003	50 dB
40dB	0.01	0.0016	40 dB
50 dB	0.0032	0.0012	30 dB

Next, the range of RL>25 dB, that uses the windowed discrete Fourier transform, has contributions due to the dimensional accuracy B_r and the logarithmic slope and deviation term A_r. In the plot shown, an off-set termination value of 20 dB is used on the 4-port reflection bridge that gives the average value of the ripple extraction histogram at -25 dBm.

Note, in ripple extraction the system operates in the homodyne mode. A large reference signal is present at the bridge detector and the smaller unknown Γ_x provides an interference pattern in the swept frequency plot histogram.

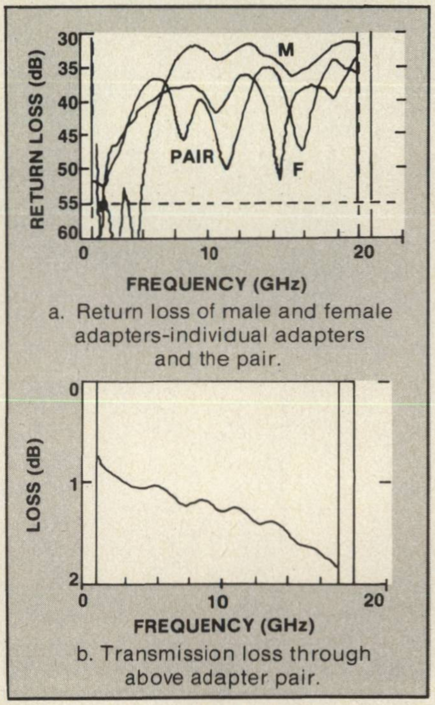
Note, the extraordinarily low noise floor that is 60 dB below the reference level created by the 20 dB offset. Thus, in measuring a return loss of 40 dB ($|\Gamma_x| = 0.01$, SWR = 1.02). The signal to noise ratio is 40 dB. This most favorable signal to noise ratio, as well as, the use of the "in situ" air-line as the impedance reference and further, the beadless LPC-7 connector at the measurement port give this reflection measurement multiple advantages over any other error corrected ANA.

To achieve dimensional accuracy corresponding to $\Delta\Gamma$ of 0.001 for a 7 millimeter air-line the outer conductor tolerance is ±0.0002" and for the inner ±0.0001". Three 30 centimeters long, 7 millimeter diameter WILTRON air-lines were measured at NBS Boulder in 1979. All lines were within the dimensional specifications and, in using various RF test procedures, tested within specifications, however, it is felt that comparison of production air-lines will be most effectively tested using DSP on RF measurements. Frequency domain test of both 30 and 40 dB return loss terminations with different air lines clearly show air-line tolerance variations at the required level of accuracy. Even more impressive is the spatial domain comparison of impedance between different physically certified reference air-lines to be shown in tabular form.

In Table 1, the worst case, sum of the errors from Figure 2 for the "ripple extraction" method of measuring small reflection coefficients, is summarized.

Measurement Of Non—Insertable Devices

An important non-insertable device that is often encountered in measurement practice, is the adapter. Data on a pair of GPC-7 to WSMA adapters is shown in Figure 3. The return loss at the 7 mm port was measured for each with the SMA port terminated by 3.5 air-line using the compensated WSMA[3] junction. The pair were measured again using air-line termination of the distant port. All three data plots are super-imposed in Figure 3a. Next, insertion loss of the adapter pair was measured



a. Return loss of male and female adapters-individual adapters and the pair.

b. Transmission loss through above adapter pair.

Fig. 3 7mm to SMA adapter pair.

and plotted in Figure 3b. Both reflection and transmission measurement configurations correspond to Figure 1a. Note the 0.01 dB peak-to-peak ripples appearing in the loss data, this correlates with the bead spacing of the adapter pair and the effect of the product of the two individual reflection coefficients.

Spatial Domain Reflectometry (Distance-To-Fault)

This measurement has been made by the pulse (or step) and swept frequency measurement methods. The second method can now be easily processed and plotted or tabulated from the Fast Fourier Transform of the swept frequency interference pattern. Again the data is windowed to vir-

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tually eliminate spurious output due to the finite interference pattern. Figure 4 shows the use of the WFFT to plot return loss on a reference transmission feed cable used by a military aircraft test facility. The cable is then reversed and the data retaken. Note the close mirror symmetry. A distributed lossy path will rarely show exact mirror symmetry.

Another promising use of the WFFT has been investigated for comparing precision air-lines. The maximum dimensional spread of the outer and inner conductor was ±0.0001" as physically measured by NBS. The outer conductor diameter profile was measured and plotted, but only the peak deviations of the inner conductor diameter were reported. The data by this method would corroborate impedance conformance of the two lines to provide >66 dB RL.

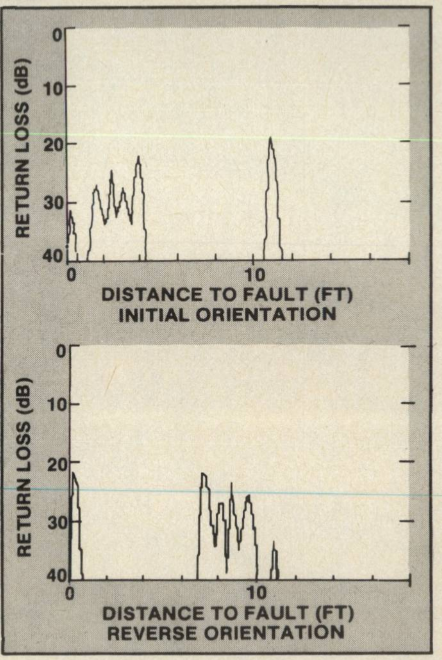

Fig. 4 Distance-to-fault measurement of a reference transmission feed cable.

Conclusion

The Scalar Network Analyzer is used on distributed network to provide swept frequency interference patterns that can be digitally processed to provide both frequency and spatial domain reflection transmission data carefully enhanced for both laboratory and field measurement applications. The high performance SANA under GPIB control by a desk computer provides high versatility by means of the various computation programs.

Acknowledgements

Robert Huenemann has been project engineer for the software and the system evolution. The distance-to-fault program was initially carried out by Gottfried Lang and Art Fore of Lang Electronics of Munich.

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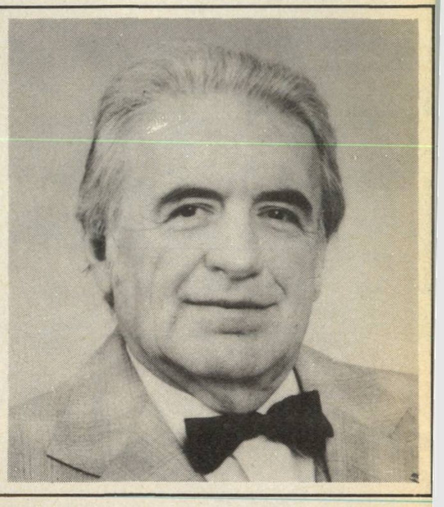

Dr. Peter Lacy, *was a founder in 1960 and now serves as Chairman of the Board of Wiltron Company, a manufacturer of electronic measurement systems and components for microwave, RF, and telecommunications applications. He received the BSEE from the University of Florida where he participated in sferics research, the operation and engineering of the University Radio station and related consulting. In the Navy, he coordinated projects in ECM on power sources and radar targets in Washington, DC, later serving on the Pacific Fleet Headquarters staff and the Naval Technical Commission to Japan. He received the MS and PhD degrees from Stanford and studied microwave noise in electron beams. At Hewlett Packard for ten years, he lead R & D on microwave tubes and developed related instrumentation. Dr. Lacy served as chairman of the MTT chapter, IEEE section, and 1966 Microwave Symposium. He has served on several national committees and is a IEEE fellow.* ■

An Improved Automatic Network Analyzer System

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Abstract

This paper describes a HP 8409 system configuration using low noise frequency synthesizers as the VTO local oscillator and RF signal sources. The minor hardware and software modifications are shown and the improved measurement accuracy and dynamic range are compared to the measurement performance of the basic HP 8409 system and the HP 8542B system

Introduction

The Hewlett-Packard 8409B/C Automated Network Analyzer (ANA) configuration provides program control of the source output frequency (source phase-locked subsystem), receiver tuning, IF gain and data conversion to produce fully error corrected transmission and reflection measurements from 0.1 to 18 GHz.

The accuracy of measurements obtained with the ANA is greatly dependent upon the accuracy and precision of the standards used in the system calibration process. The calibration process characterizes the inherent impedance related measurement errors in the ANA system.

Measurement standards are required to verify the measurement accuracies and to detect any deterioration in system operation. Since 1969, the Calibration Services Department at TRW has maintained and used measurement standards to maintain measurement accuracies and to establish confidence in measurements performed with ANA systems.

The attenuation standards are coaxial attenuators with APC-7 connectors. Values of attenuation are 3, 10, 20, 30, 40, 50, and 60 dB. The attenuators are periodically calibrated by the National Bureau of Standards and the Primary Standards Section of TRW's Calibration Services Department.

The reflection standards, manufactured by Hewlett-Packard, have APC-7 connectors. Nominal VSWR values of the mismatches are 1.1, 1.5, 3.0 and 4.0. They have been calibrated by the Hewlett-Packard Primary Standards Laboratory and TRW's Calibration Services Department.

The 8662A is also used as the VTO synthesizer (local oscillator) when operating in the 2.0 to 18.0 GHz frequency range. The original VTO synthesizer (3335A) is still used as the VTO when operating from 0.1 to 2.0 GHz. It is switched into the 8672A to replace

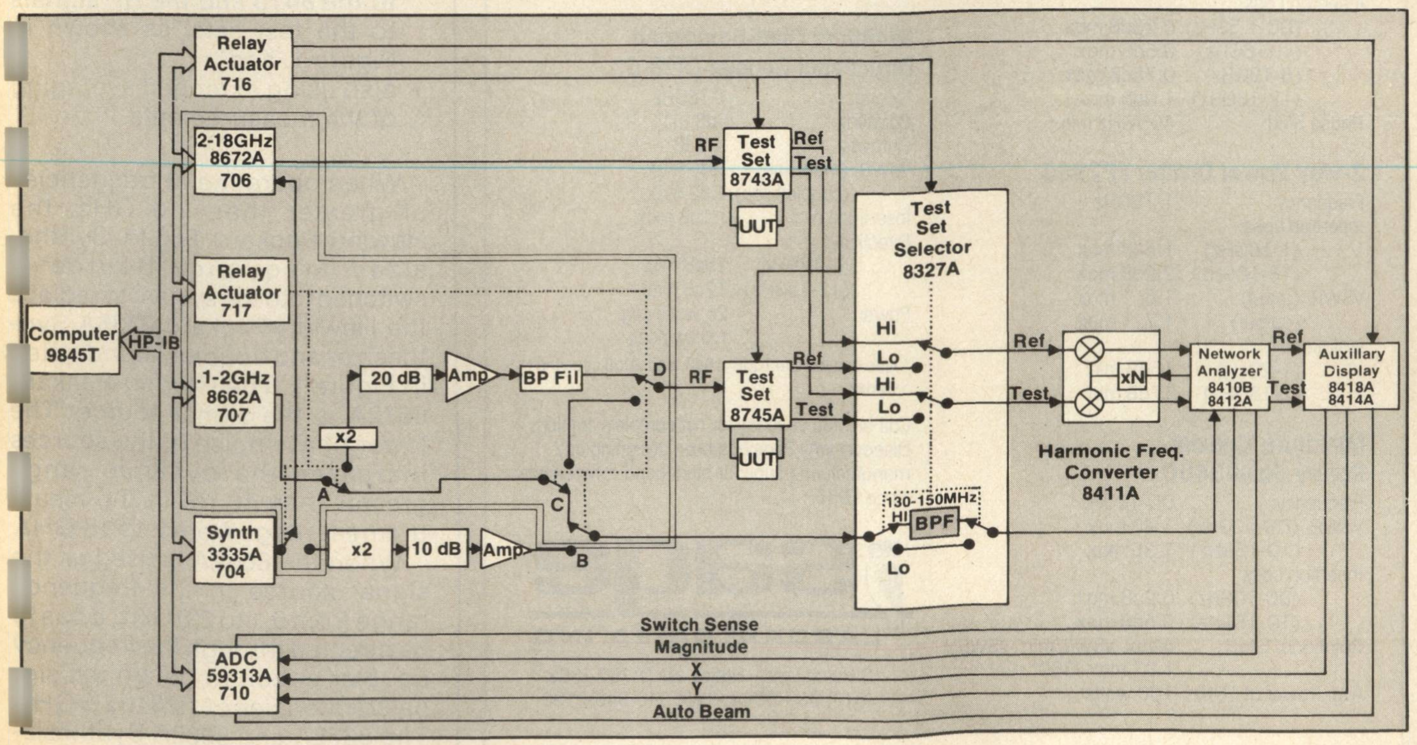


Fig. 1 TRW calibration services 100 MHz to 18 GHz automatic network analyzer.

[Continued on page 66]

[From page 65] **SYSTEM**

the internal 20 to 30 MHz VCO when operating from 2.0 to 18. GHz. This provides frequenc resolution out of the 8672A equal to the 3335A. The frequency reso- lution and repeatability of the sys tem is 0.1 Hz for all operating fre quencies. The 10 MHz reference oscillators of the three synthesiz ers are locked together. The fre quency stability of the system is 5 x 10^{-10}/day. It can be locked to an external frequency standard, suc as a cesium beam type, fo improved long term frequency accuracy. This is an improvement over the standard phase-locke 8409B/C which provides pro grammed frequency accuracy of about ±1 part in 10^6 plus 5 kH and repeatability within 100 Hz.

Dynamic Range Improvement

The comparison data in Table indicates that the system ca measure attenuation values to 80 dB. The measurement accuracy at 80 dB is comparable to the orig inal specifications for measure ment at 60 dB.

The improvement in dynami range is obtained essentially b using:

- synthesizers with lower phase noise characteristics to gene ate the 130 to 150 MHz signals to the 8410 and the RF signals to the test sets, as shown i Figure 1, and
- also using extended averaging of the measurements.

When operating at frequencie of greater than 2.0 GHz, the Hewlett-Packard 8662A Synthe sized Frequency Source switched into the system to replace the Hewlett-Packard 3335A Syn- thesizer and doubler, as indicate in Figure 1. The Hewlett-Packar 8672A is the signal source. The lower phase noise of the sources increases the dynamic rang greater than 10 dB in the meas urement range from 2 to 18 GHz.

When the 8662A is used as the signal source in the frequenc range from 0.1 to 2.0 GHz, it has to be directed through the frequency doubler circuit to obtain the sig nal frequencies of 1.28 to 2.0 GH The 8672A and 8662A Synthesiz- ers were chosen for this applica-

[Continued on page 6

[From page 66] **SYSTEM**

tion because of their lower phase noise charcteristics and overall performance capability in this automated system.

Measurement Uncertainty Improvement

The measurement uncertainty improvement results from both hardware and software modifications to the original system and program. The hardware improvements result from the much lower LO and signal phase noise, frequency accuracy, resolution and repeatability and very careful system alignment and maintenance procedures. The software improvements include extended averaging (to 512 samples) and improved "quadrature detector" calibration procedure.

Additional software is being developed to provide the basic flexibility and capability of the original Hewlett-Packard 8542B ANA. However, the special plotting, printing and measurement routines do not enhance the basic system measurement accuracy.

It has been TRW's experience that the Hewlett-Packard 8542B could be maintained, with considerable effort, to measure within the published accuracy specifications. The latter 8409B (and C) versions have been consistently more accurate than the 8542B, especially when using the "extended averaging" software. However, it is noted that Hewlett-Packard does not actually specify a system measurement accuracy for the 8409B/C. The standard 8409B/C system falls in between the uncerainty values in Table 1 for the 8542B and the TRW modified system. The 8409B/C has an effective dynamic range for insertion measurements of greater than 70 dB when using the above mentioned software. The hardware improvements illustrated in Figure 1 increase this range to greater than 80 dB.

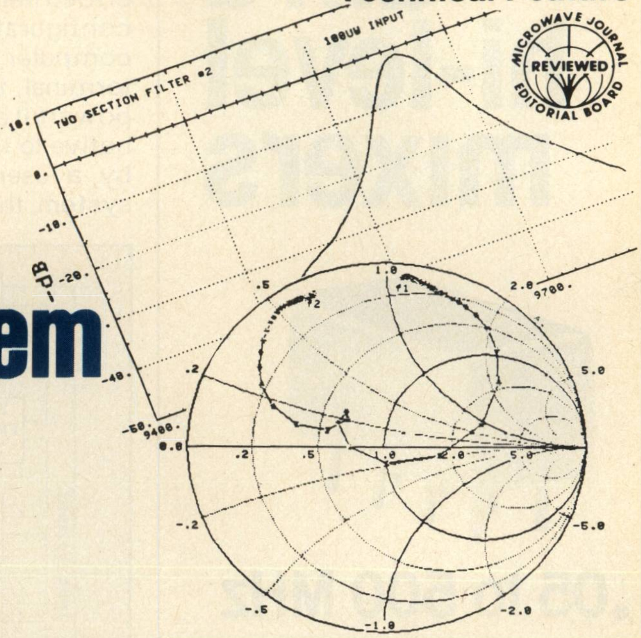
The uncertainty values stated for the TRW system were derived statistically. The ANA standards were measured on the ANA on five separate seesions over a period of several weeks. Five individual measurements (disconnect and reconnect) were performed each session. A complete ANA maintenance, including alignment adjustments, was performed during the evaluation. The uncertainty values include random errors and long term system related drift errors. ■

TABLE 1
AUTOMATION
TRW CSD/MED ANA MEASUREMENT UNCERTAINTY

FREQUENCY (GHz)	ATTENUATION (dB)	UNCERTAINTY (dB)	HEWLETT—PACKARD 8542B ANA UNCERTAINTY
0.10 - 2.00	10	+0.02	+0.12 (0.1 - 12.4 GHz)
2.00 - 18.00	10	+0.03	+0.16 (12.4 - 18.0 GHz)
0.10 - 2.00	20	+0.02	+0.13 (0.1 - 12.4 GHz)
2.00 - 18.00	20	+0.04	+0.18 (12.4 - 18.0 GHz)
0.10 -2.00	30	+0.03	+0.15 (0.1 - 12.4 GHz)
2.00 - 18.00	30	+0.05	+0.22 (12.4 - 18.0 GHz)
0.10 - 2.00	40	+0.03	+0.20 (0.1 - 12.4 GHz)
2.00 - 18.00	40	+0.08	+0.28 (12.4 - 18.0 GHz)
0.10 - 2.00	50	+0.05	+0.30 (0.1 - 12.4 GHz)
2.00 - 18.00	50	+0.10	+0.50 (12.4 - 18.0 GHz)
0.10 - 2.00	60	+0.06	+0.70 (0.1 - 12.4 GHz)
2.00 - 18.00	60	+0.20	+1.00 (12.4 - 18.0 GHz)
0.10 - 2.00	70	+0.15	HP 8542B WAS NOT SPECIFIED ABOVE 60.0 dB.
2.00 - 8.00	70	+0.25	
8.00 - 18.00	70	+0.30	
0.10 - 2.00	80	+0.35	HP 8409B/C ANA SYSTEMS ARE NOT SPECIFIED BY HP.
2.00 - 8.00	80	+0.50	
8.00 - 18.0	80	+1.00	

APC-7 COAXIAL CONNECTORS AND 12-TERM ERROR MODEL.

Interactive ANA Measurement System



B. Perlman, D. Rhodes,
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Introduction

Microwave network analyzers are routinely used in all phases of microwave engineering, from the initial design stages to the production line testing of final assemblies. With the rapid growth in the microwave field, the need for faster, more accurate measurements has led naturally to the development of automated microwave network analyzer systems. Until recently, the HP 8542 system was available to meet this need; however increasing costs and obsolescence of certain instruments dictated that a new configuration be developed. In an effort to reduce the system cost and complexity, Hewlett-Packard developed the HP 8409 system along with instrument control and accuracy enhancement software [1,2]. This system, comprised of mostly "off-the-shelf" hardware, compromised the capabilities of the HP 8542 by using a desktop calculator/controller in place of the HP 2100. In many applications the desktop calculator/controller is inadequate. The ability to access measurement data from other programs (e.g. CAD), and the advantages of a larger system's speed and resources (e.g. database methods, local area networking) demand more sophisticated computer power. We describe here an alternative control program for the HP 8409 system hardware which offers many advantages over the standard package.

The controlling program, named PLANA/1000 (Phase-Locked Automatic Network Analyzer/HP 1000), is written in FORTRAN IV to replace the HP 11863D accuracy enhancement softwarprovided with the standard system [3,4]. A photograph of an improved HP 8409B system is shown in Figure 1. The block diagram of Figure 2 identifies the specific network analyzer and related hardware and includes an HP 1000F minicomputer as the system controller. The principal differences between the system shown and the standard system is the addition of an HP 8746 S-parameter test set, programmable power supplies for device biasing, and substitution of the HP 1000F for the HP 9845 calculator, normally provided as the system controller. An optional color graphics display system has been added to provide real-time interactive color graphics.

The use of the HP 1000 minicomputer as the system controller and the optional color graphics system represent the unique hardware differences between the commercially available HP 8409 system and what is to be des-

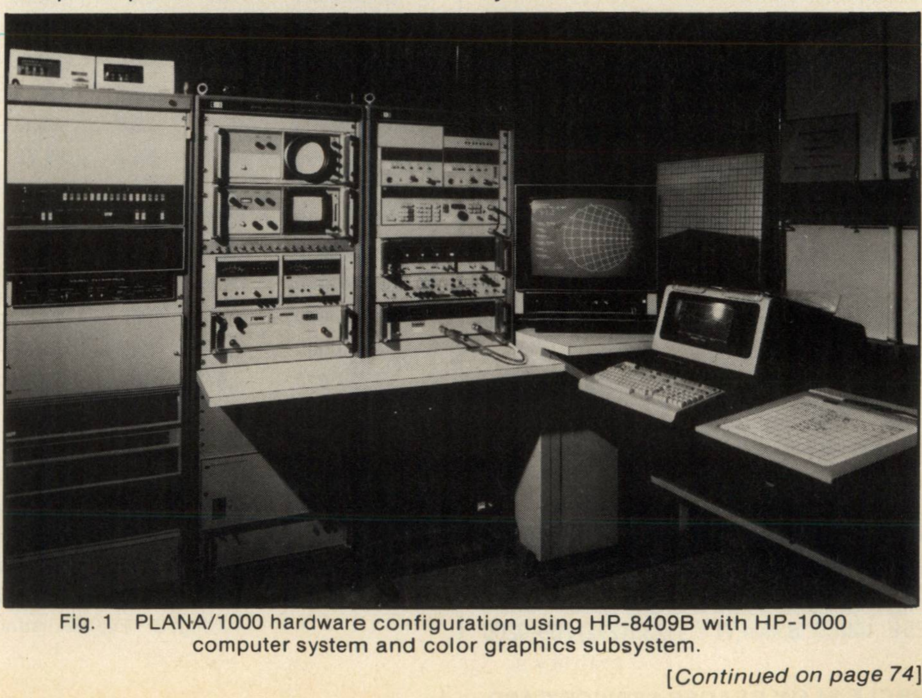

Fig. 1 PLANA/1000 hardware configuration using HP-8409B with HP-1000 computer system and color graphics subsystem.

[*Continued on page 74*]

[From page 73] **ANA**

cribed here. In one of its standard configurations, consisting of the computer, hard disc, and graphics terminal, the HP 1000 provides a powerful and cost-effective alternative to the HP 9845. Supported by a user-configured operating system, the HP 1000 permits program development in high level languages and multi-user capabilities. The multi-programming feature means that the computer can control several network analyzer systems concurrently and/or independently support other users while measurements are taking

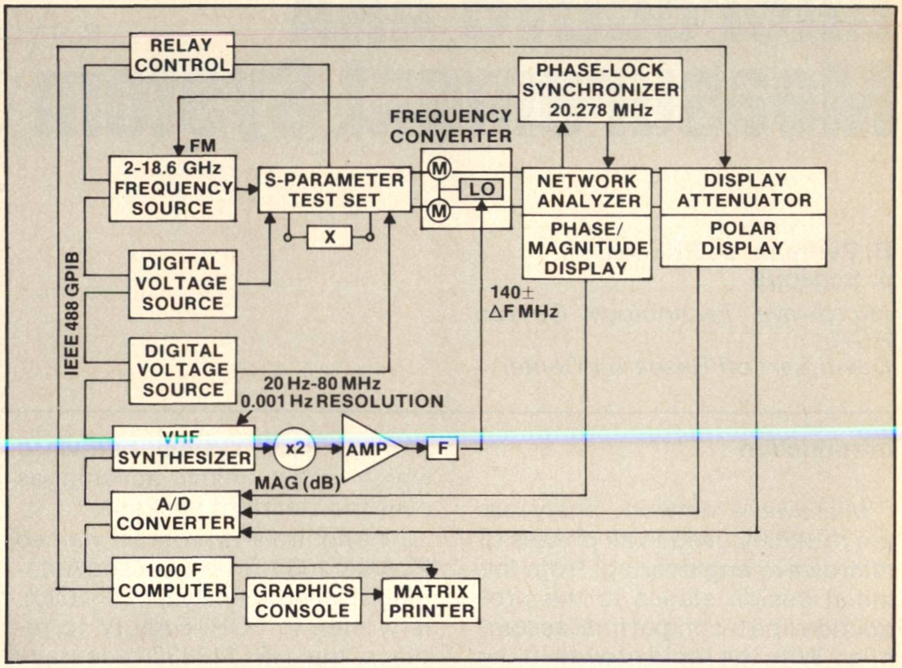

Fig. 2 Block diagram of PLANA/1000 hardware.

FREQ	S11		S21		S12		S22	
(MHz)	(DB)	(ANG)	(DB)	(ANG)	(DB)	(ANG)	(DB)	(ANG)
9450.0000	-.67	19.1	-46.93	127.5	-41.15	107.1	-.10	28.0
9470.0000	-.58	16.4	-46.26	141.4	-41.06	112.6	-.10	25.4
9490.0000	-.63	13.3	-46.67	125.5	-41.29	124.1	.03	21.7
9510.0000	-.59	10.3	-41.88	105.9	-39.55	113.4	.10	18.1
9530.0000	-.67	6.2	-35.08	105.0	-36.28	98.9	.26	15.2
9550.0000	-.75	1.8	-32.27	105.3	-32.19	100.3	.39	11.7
9570.0000	-.86	-3.8	-29.28	100.2	-28.53	99.4	.51	8.0
9590.0000	-1.09	-11.0	-24.75	92.2	-23.94	91.0	.64	2.3
9610.0000	-1.29	-22.8	-18.52	81.1	-18.02	77.9	.66	-7.4
9630.0000	-3.49	-55.7	-9.72	47.1	-9.66	47.5	.17	-28.8
9650.0000	-14.81	90.4	-2.10	-37.3	-2.85	-40.5	-7.54	-77.1
9670.0000	-10.19	69.9	-2.94	-139.3	-3.80	-132.9	-6.77	120.4
9690.0000	-2.24	51.4	-11.48	156.1	-10.73	160.0	-.15	62.3
9710.0000	-1.01	34.4	-19.30	135.8	-17.70	137.8	.20	41.0
9730.0000	-.70	24.7	-24.84	122.0	-22.90	128.6	.22	31.5
9750.0000	-.76	18.5	-29.28	117.1	-26.51	120.8	.25	26.1
9770.0000	-.84	13.9	-33.74	124.9	-30.00	118.8	.21	22.6
9790.0000	-.88	10.2	-37.44	111.3	-34.79	115.8	.27	19.2
9810.0000	-.91	6.9	-37.05	78.6	-38.11	116.4	.34	16.4
9830.0000	-.88	3.3	-39.22	66.2	-35.53	134.2	.44	14.4
9850.0000	-.84	.1	-40.18	45.8	-36.71	140.6	.55	11.6

Reference Planes: RP1 = 0.000cm, RP2 = 0.000cm

Fig. 3 Typical listing of measurement data.

place. Perhaps the most significant advantage in using the HP 1000 as the system controller is the ease of establishing a data base of corrected measurement data and the ability to access those data from other programs and terminals for use in either computer-aided design or production environments.

Program Description

PLANA/1000 incorporates all the features of the HP calculator-based control program plus much more. Included are five calibration error correction models, device de-embedment algorithms, extensive listing and plotting routines (including color graphics), disc and tape file management, complete operator control over all the instruments controlled via the HP-IB (IEEE STD. 488) interface bus, and a mnemonic interpreter to allow simple English command strings.

PLANA/1000 can accommodate up to 81 test frequencies which may be specified in a number of bands, e.g. from 2 to 8 GHz by 1 GHz steps, etc. This allows one to measure over a range and focus on part(s) of it for greater detail. All data acquisition employs accuracy enhancement routines such as adaptive averaging, phase-lock checking, and quadrature error correction. These reduce errors associated with low level signals, frequency drift, and polar display non-linearity. All calibration data, as well as the latest device measurement data are automatically saved on disc. In addition, the entire state of the program is automatically saved upon completion of each measurement. This enables one to restore the program state if it is inadvertently terminated and insures data integrity should the system fail unexpectedly.

Calibration

PLANA/1000 offers a choice of five modes of system calibration. For reflection measurements, a 3-vector model provides full error correction for directivity, source match, and frequency response for one-port measurements. For quick transmission measurements, a simple transmission norma-

[*Continued on page 76*]

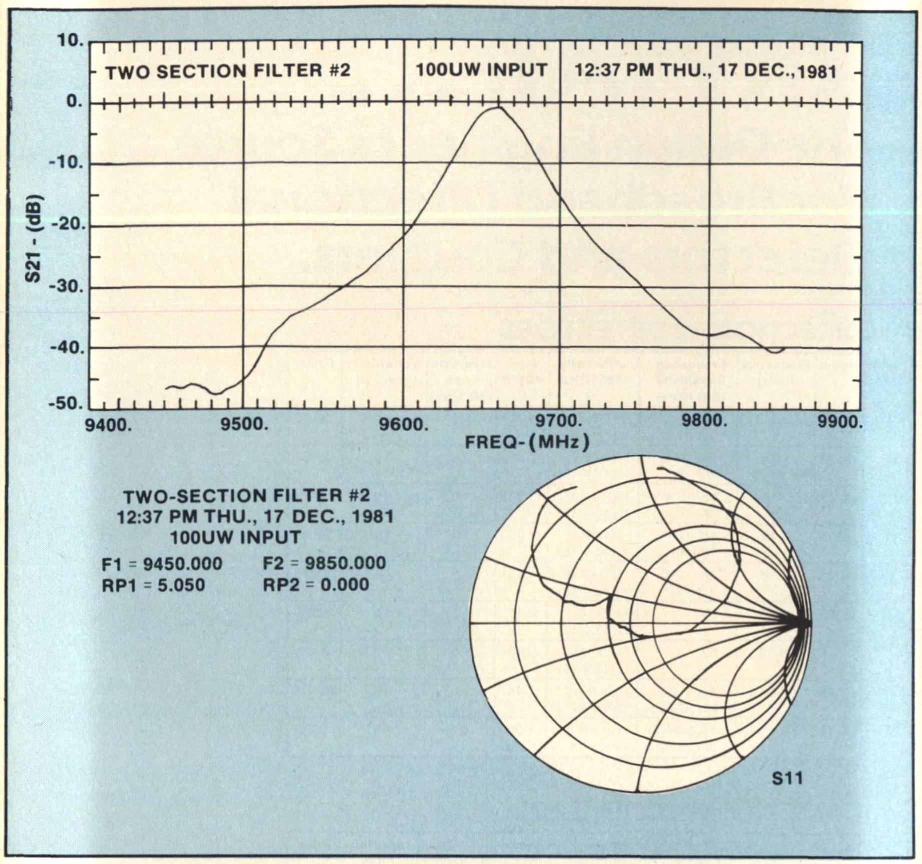

Fig. 4 Examples of video graphics on the HP-2648. a) Plot of S_{21} (dB) versus frequency, b) Smith Chart display of S_{11}.

lization correction can be performed. A 6-vector model includes the 3-vector model plus forward transmission tracking, load match, and port isolation terms. Two full error correction models are available for forward and reverse characterization: one incorporates the 6-vector model in both directions, the other is the Thru-Short-Delay (TSD) procedure [5] which is currently under development. All models except TSD use shorts, a choice of opens or offset shorts, and fixed or sliding loads as the calibration standards. For open circuits, correction for the frequency dependent effective capacitance is performed based on connector type (APC-7, SMA, etc.). For offset shorts, the program chooses an appropriate standard offset length to use for a particular frequency octave and prompts the user accordingly, or the user may specify the offset. The TSD method uses only a short, a thru connection, and a delay (a longer thru), thus eliminating the need for opens, offset shorts and loads.

Device Measurement

PLANA/1000 has three modes of device measurement; normal, continuous, and real time. In the normal mode, measurements are performed at all test frequencies, the data are corrected for system errors and are ready for listing or plotting. The continuous mode performs the device measurement loop repetitively, allowing the user to update the data listing or plot after each run. The real time mode is a special form of the continuous measurement mode which utilizes the color graphics display. In this mode, a reflection or simple transmission measurement is performed, corrected, and displayed on the color monitor as the data are acquired. Also, the normal measurement rate of about three points per second is increased to about seven per second: the result is a dynamic display of corrected S-parameter data (S_{11} or S_{21}). This allows the user to perform operations such as device tuning while measurements are taking place, and to see the corrected measurement results

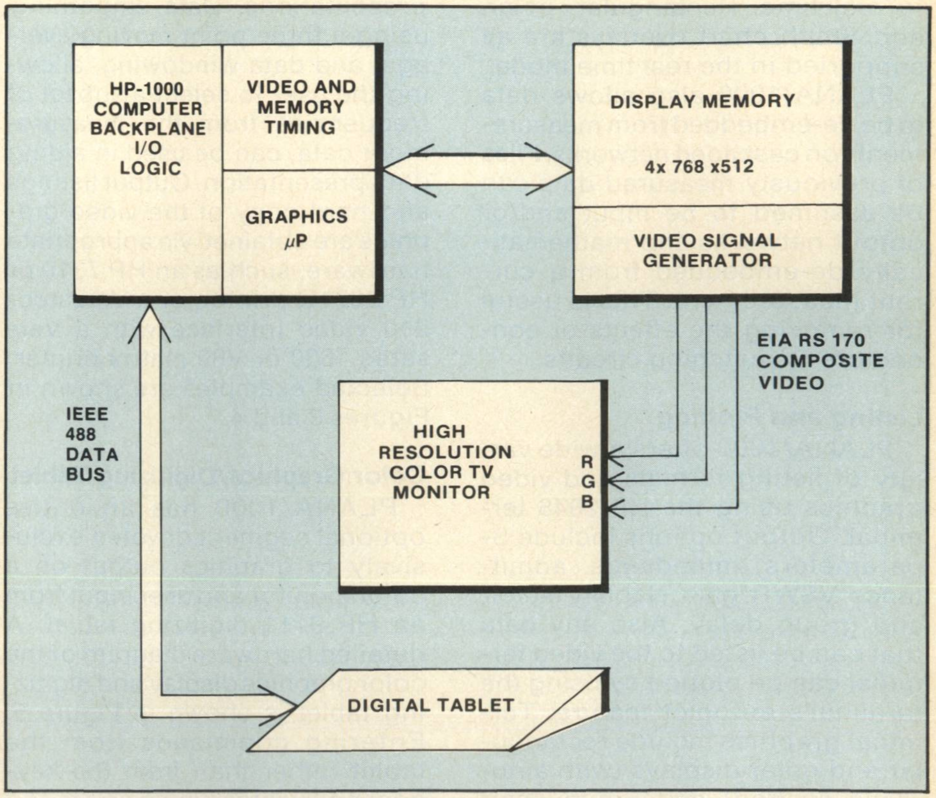

Fig. 5 Block diagram of color graphics subsystem. The graphics controller provides a TV presentation of 768 by 512 pixels with up to 8 colors plus black and white. The digitizing tablet is interfaced via the IEEE-488 bus and is refreshed at a rate of 20/sec, providing a highly interactive display capability.

[Continued on page 78]

in real time. Rectangular, polar, and Smith chart overlays are all supported in the real time mode.

PLANA/1000 also allows data to be de-embedded from measurements on cascaded networks. Files of previously measured data can be assumed to be input and/or output networks and mathematically de-embedded from a current measurement. This is useful for removing the effects of connectors or matching circuits.

Listing and Plotting

PLANA/1000 offers a wide variety of listing formats and video graphics using the HP 2648 terminal. Output options include S-parameters, impedance, admittance, VSWR, gain, stability factor, and group delay. Also any data that can be listed to the video terminal can be plotted by using the terminal's autoplot feature. Terminal graphics include rectangular and polar displays (with automatic scaling) and Smith chart presentations. Data smoothing, using a three point moving average, and data windowing, allowing the user to select a subset of frequencies from the measurement data, can be used in aiding data presentation. Output listings and hard copy of the video graphics are obtained via appropriate hardware, such as an HP 7310 or HP 2671G printer, or a Versatec-210 video interface with a Versatec 1600 or V80 matrix printer. Selected examples are shown in Figures 3 and 4.

Color Graphics/Digitizing Tablet

PLANA/1000 has an entire optional segment devoted exclusively to graphics output on a color monitor and user input from an HP 9111 digitizing tablet. A detailed hardware diagram of the color graphics display and digitizing tablet is shown in Figure 5. Entering commands from the tablet rather than from the keyboard alleviates typing errors and saves time for the designer. Along the top of the tablet are a series of sixteen "command softkeys"; presently each one can represent one command. To execute a command, the designer touches it with the digitizing wand and a set of "menu items" (in the large area below the "command softkeys") associated with that command is then activated. For example, if the designer would like to have a Smith chart of S_{22}, he would first choose the softkey marked "CHART". This activates all the items pertaining to the types of graphs that can be displayed. He then touches the item labelled SMITH and a Smith chart appears on the color monitor. A similar procedure is used to select the S-parameter (Figure 6). Having a softkey activate other areas of the tablet prevents a series of unwanted commands from being executed if the designer inadvertently moves the wand across the tablet.

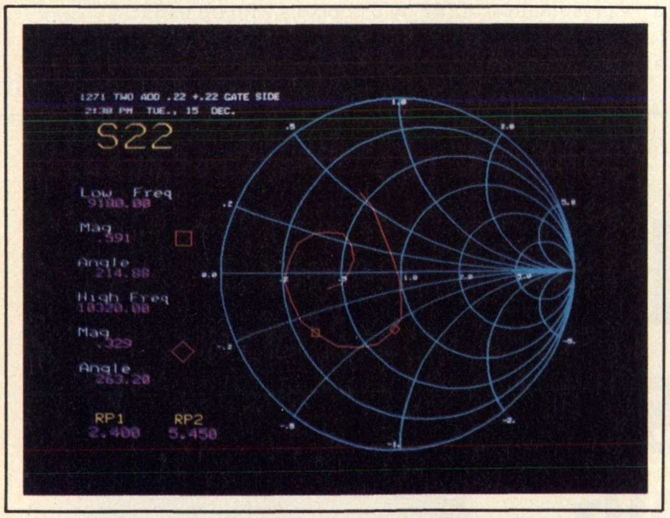

Fig. 6 Color display showing S_{22} with a Smith Chart overlay.

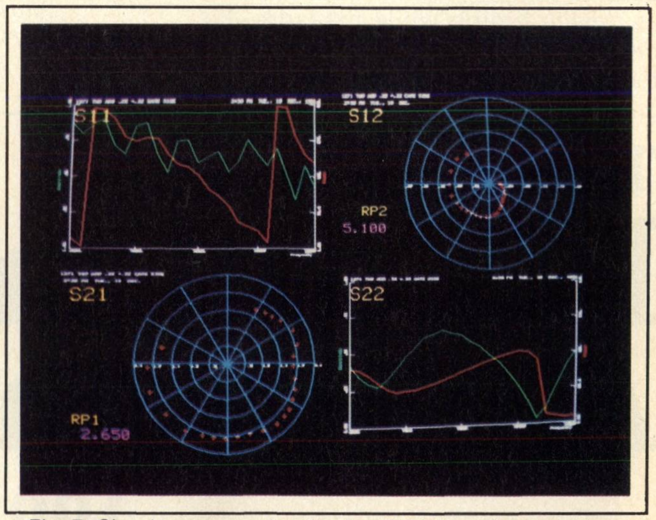

Fig. 7 Simultaneous color display of all four S-parameters

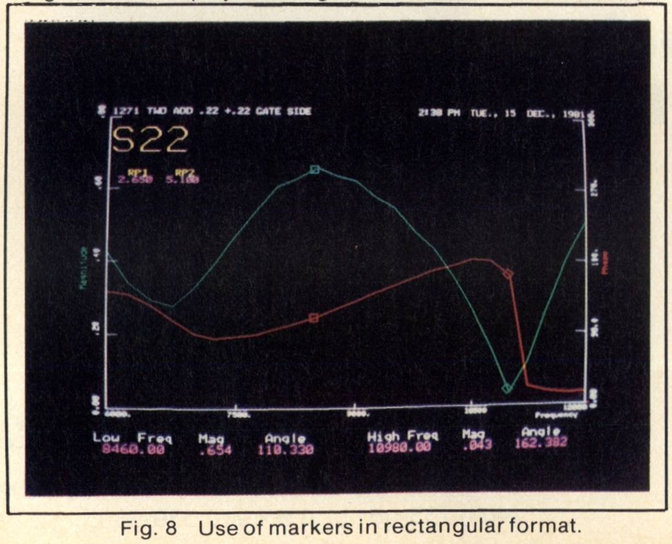

Fig. 8 Use of markers in rectangular format.

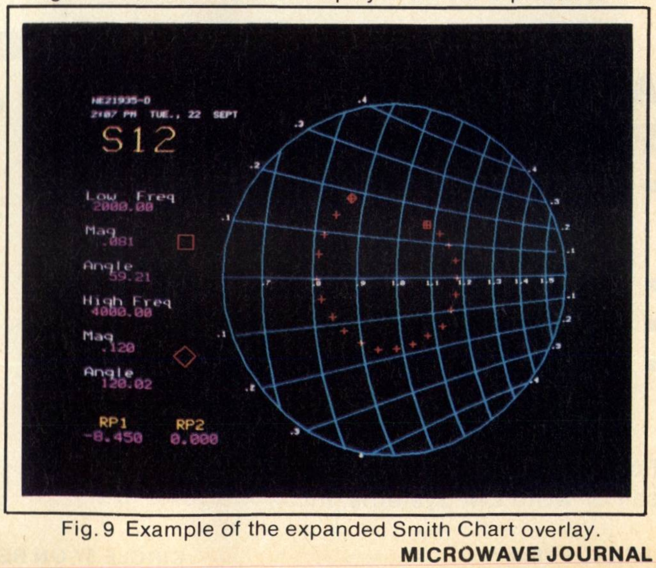

Fig. 9 Example of the expanded Smith Chart overlay.

But the digitizing tablet does more than simply act to eliminate typing; its biggest advantage is one of interaction. Here the designer can perform interactive commands that cannot be done through the keyboard. For example, when the sofkey "ROTATE" is chosen, a set of eight arrows is activated in the menu area. The arrows are associated with either port 1 or port 2 and the direction and speed of rotation. Of course, while the reference plane is being changed the color monitor is dynamically displaying the result. This is the case for all instructions; the color monitor instantaneously reacts to any graphics command.

The color monitor provides many different types of output, some of which have already been mentioned. The various types of graphs currently available are: Smith, expanded Smith, polar, and rectangular magnitude and phase charts (color allows both to be plotted simultaneously). There are also formats which have graphs of all four S-parameters simultaneously on four different charts, (Figure 7) in either rectangular or polar form. Additional examples of color graphics output are shown in Figures 8 and 9. Along with each graph are two frequency markers which can be moved using a tablet command. At any current position, the values of frequency, magnitude, and phase are displayed for each marker.

Conclusions and Future Plans

A highly interactive, user-oriented, automatic network analyzer system has been developed using standard HP 8409 hardware, an HP 1000 disk-basd minicomputer, and a color graphics subsystem. PLANA/1000 offers many advanced features not found in the standard calculator-based HP 8409 package. The PLANA/1000 software provides an interactive operator interface for hardware calibration and device measurement, a choice of several error correction algorithms, control of the phase-locked frequency sources and other instrumentation, listing and plotting of data in a variety of formats, disc and tape file management. The additional capabilities unique to PLANA/1000 include real time display of corrected S-parameter measurements, tablet-driven commands, and color graphics output of measured data.

The present system remains very flexible and expandable so that special applications can be easily accommodated. Current work continues in order to extend digitizing table input and color monitor output. Plans are included to develop at least some entirely new segments as well: a time domain analysis segment, a macro-command processing segment, and a data base managing segment. The intelligent time domain analyzing segment can provide important spacial information which in some cases can be of great use to the designer[6]. The macro-command processor can reduce the drudgery of repetitively performing the same sequence of inputs. Here a series of commands can be defined as a "new command" and remembered by the computer. Executing this newly defined command causes this entire sequence of commands to be executed. Indeed each potential user can individually define the macro commands that he most often uses, or the engineer can exactly define the testing sequence and output format with a macro definition for a particular device. Then a tester can perform repetitive device measurements with just one command. The task of the data base manager is to record and retrieve data about each measurement including device type, bias conditions, validity of the measurement and other attributes. The data base would prevent users from duplicating previous work and would facilitate project coordination, particularly in a manufacturing environment. For example, one might query the data base manager about previous work on amplifiers in the 12 to 13 GHz region with greater than 10 dB gain, and the data base manager will respond that someone built an amplifier of that type two years ago.

All of these ideas about the future of PLANA/1000 represent a continuing effort to improve and

[Continued on page 80]

[From page 79] **ANA**

expand upon the current capabilities.

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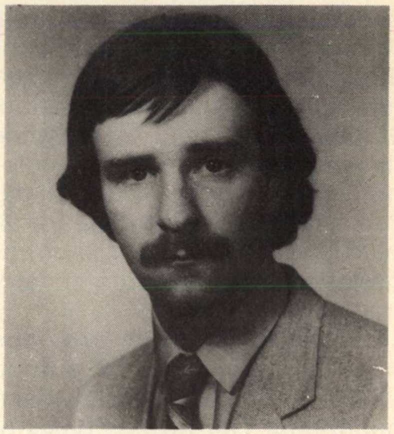
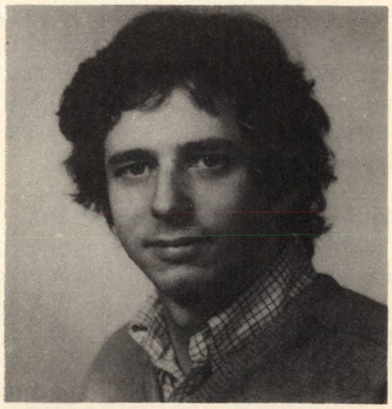
He is presently Manager of CAD and Testing in the Microwave Technology Center at the RCA David Sarnoff Research Center, Princeton, NJ. His group is responsible for the development of computer-aided design, advanced automated measurement techniques and other computer aids to engineering.

He has published more than 30 technical papers in the fields of solid-state devices, microwave networks and CAD and has received four patents. In 1969, he received an engineering achievement award for advanced device development, and in 1970, he shared an RCA Laboratories Outstanding Achievement Award for his part of a team effort in the development of wideband transferred electron amplifiers. In 1975, he received an individual achievement award for his contribution to computer-aided design and laboratory automation.

Dr. Perlman is a member of Sigma Xi, the IEEE, and a registered professional engineer in the State of New York. He is a member of the IEEE sub-groups on Microwave Theory and Techniques and Instrumentation and Measurements. He is also a member of the ACM and the computer society. He is a founding member and current President of the HP-1000 International Users Group.



David L. Rhodes, *received the B.S.E.E. degree from Rutgers University in 1980 and is presently working toward a M.S.E.E. degree at Princeton University under the RCA Graduate Study Program. He joined the Microwave Technology Center of RCA David Sarnoff Research Center in 1980 and has been working in the field of computer simulation and modeling for microwave CAD. He is concurrently active in computer graphics and developing highly-accurate models for trans-mission-line structures, power dividers and couplers.*



Jonathan L. Schepps, *received the B.A. degree in Biology from Hofstra University in 1976 and the M.S.E. and Ph.D degrees in Bioengineering from the University of Pennsylvania in 1978 and 1981, respectively. His graduate work involved the use of the microwave network analyzer for accurate dielectric measurements on biological materials and an analysis of the biophysical mechanisms responsible for the measured properties.*

Since July 1981, he has been working for the Microwave Technology Center at RCA Laboratories, Princeton, NJ in the area of microwave design and measurement automation. ■

Automatic Scalar Analyzer Uses Modern Technology

Paul Spenley and Will Foster
Marconi Instruments Ltd.
Microwave Products Division,
Stevenage, England

A new instrument now makes possible truly automatic scalar analysis. A microprocessor enables scalar measurements to be displayed in an optimum form without recourse to manually set amplitude offset controls. The results can be displayed on a CRT together with alphanumerics for operator convenience and hard copy recording. The use of programmed memories rather than log amps for correction of out of square law and temperature effects minimizes drift and temperature changes.

Detectors

The 6500 Scalar Analyzer has the conventional 3 channels and uses a DC system for the detectors. This overcomes the disadvantage of inserting a PIN modulator and modulation assymetry errors. It is difficult with a modulated system to achieve high power testing without compression - a measurement increasingly of importance with GaAs FET amplifiers and high level mixers.

Both the modulated and DC systems give rise to errors due to temperature changes and deviations from true square law response. Figure 1 shows a typical power error reading that results when the temperature of the chip is varied about 25° C. Figure 2 shows the deviation from square law response as the incident power on the chip is increased.

The 6150 series of Detectors used with the 6500 Scalar Analyzer use zero bias silicon Schottky Barrier Diodes. These have been characterized using extensive measurements made with the GPIB ATE system shown in Figure 3. A correction table to account for square law deviations is held in EPROM within the 6500. A temperature sensor mounted in the detector head is used to provide data for temperature correction.

To achieve high accuracy in absolute power measurements and interchangeability of detectors, tight limits are required on the square law deviation. These are met by having low chip to chip variation in response over dynamic range and by normalizing the detector output using a load resistor.

Since the i-v characteristic of the diode is given by

$$i = f(v) = I_s[e^{\frac{V}{nKT}} - 1]$$

the saturation current I_s and ideality factor n are checked for each batch of chips to ensure consistent performance.

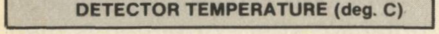


Fig. 1 6511 Detector temperature error.

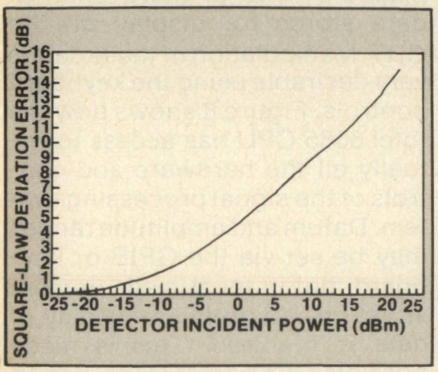


Fig. 2 6511 Detector Square-Law deviation.

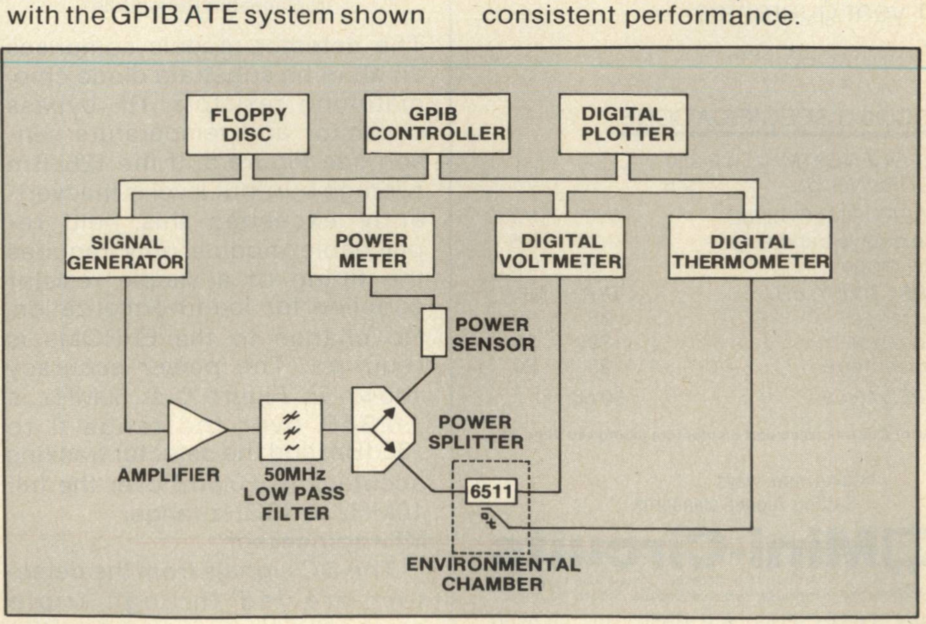


Fig. 3 6511 Detector error data aquisition system.

[Continued on page 84]

[From page 83] **SCALAR ANALYZER**

The DC equivalent circuit of the detector and the diode parasitics have been deduced and CAD techniques used to obtain optimum values for the thin film matching resistor network shown in Figures 4a & b thus allowing the broadband VSWR of 1.2:1, .04 to 8GHz, 1.5:1 8 to 18GHz and ±0.5dB flatness specification to be met.

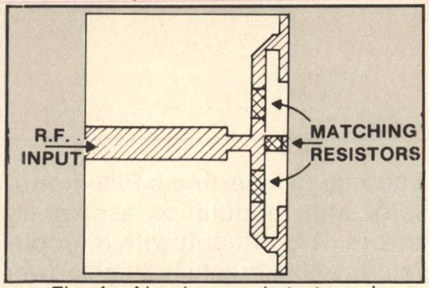


Fig. 4a Aluminum substrate and matching elements

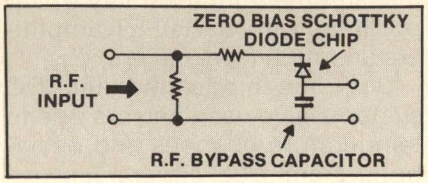


Fig. 4b Circuit of detector and matching elements

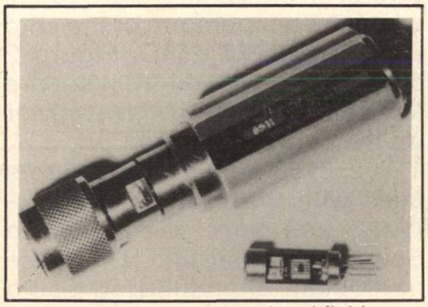


Fig. 5 Detector head and field replaceable RF module

The detector module comprises an alumina substrate diode chip, matching resistors, RF bypass capacitor and temperature sensor, see Figure 5. If the +26dBm average burnout level is inadvertently exceeded this field replaceable module only requires the fitting of a simple resistor supplied for load normalization. No change to the EPROMs is required. The power accuracy shown in Figure 6 at 50MHz is ±0.3dB over the range 0 to -30dBm and the detector tracking accuracy is ±0.5dB over the full 10MHz to 18GHz range.

Microprocessor

The DC signals from the detectors are fed through triple screened low loss cables to the 6500 input ports. Figures 7a & b show the arrangements of each signal channel.

To achieve the 0.01dB resolution over 66dB dynamic range the microprocessor controls the 3 adjustable gain stages in order that the dc level fed to the successive approximation Analogue/Digital/Converter is held in a constant 10dB window. The microprocessor also can null out unwanted effects of range switching spikes from the chopper and time variations through an auto null routine at each range change.

The digital output from the ADC needs to be converted to logarithmic form. Standard but potentially inaccurate/unstable analog methods of DC to log conversion via logarithmic amplifiers is avoided by the use of microprocessor conversion technique. In the 6500 the DC level digital output from the ADC addresses a table of data held in EPROM which converts the data to logarithmic form.

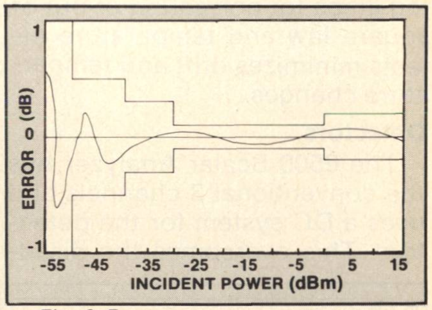


Fig. 6 Power accuracy at 50 MHz

Use of a look-up table data held in EPROM is also made at this stage to remove detector RF to DC conversion errors found out of the square law region, and to correct for errors due to ambient temperature variation.

The now accurate information obtained after correction is then placed in one of the 3 channel data stores for display on the CRT. Manipulation of these data is very desirable using the keyboard controls. Figure 8 shows how the Intel 8085 CPU has access to virtually all the hardware and controls of the signal processing system. Datum and amplitude ranges may be set via the GPIB or keyboard, but in most measurement situations an optimum display of data is required. This is made possible using an AUTO function which places the CRT traces on

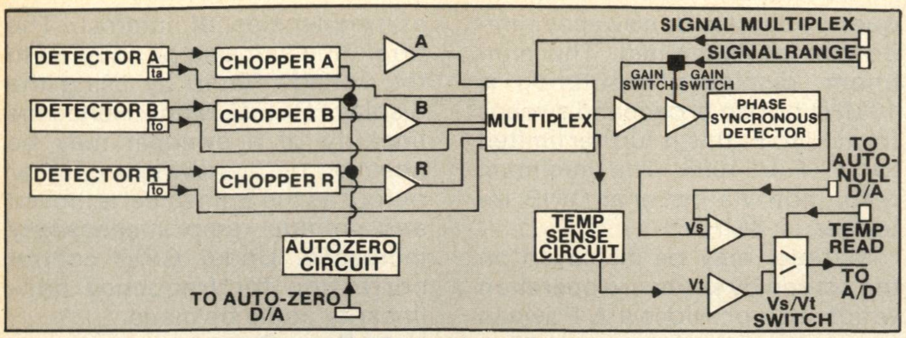


Fig. 7a Input circuitry

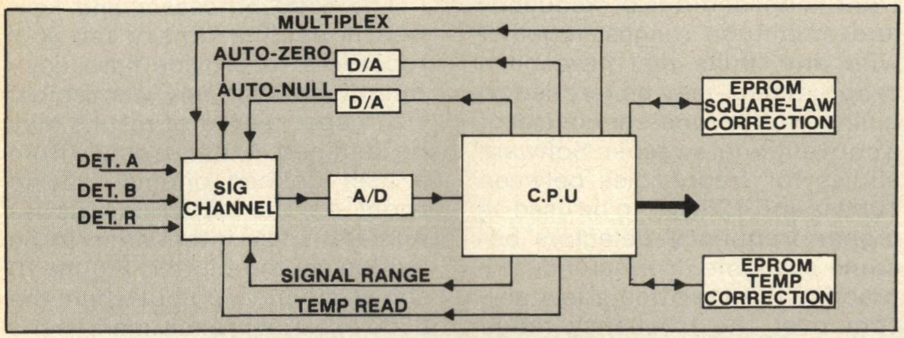


Fig. 7b Data correction circuit.

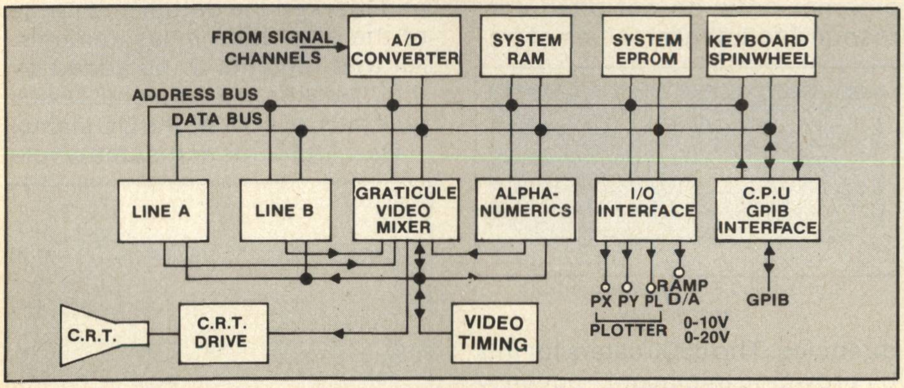


Fig. 8 6500 amplitude analyzer block diagram.

the optimum scales and labels them on the screen with a powerful set of alphanumeric graphics. Low and high limits may be set on both measurement channels and a device under test exceeding either or both of these limits results in error messages being flashed on screen and on SRQ sent via the GPIB.

Keyboard operation provides main operating programs as well as interrupt routines. The main programs are held in 25K byte EPROM with 12K byte RAM for temporary storage. Pressing a key at any time causes the processor to execute a special section of code which corresponds to the key function. If the key causes no change to the current measurement sequence, control reverts to the main program.

Display

The 6500 generates a 12 bit voltage ramp output from a D-A converter controlled by the processor. This is used to drive the frequency of the RF source via the external sweep input. The 6500 is thus in control of the RF source since for a specific voltage input, a given Sweeper or Signal Source produces a specific output frequency.

The ramp outputs provided are 0-10V and 0-20V for solid state oscillator based and BWO based RF sources. The ramp voltage is initially set to zero, and the sweeper minimum frequency entered via the keyboard. This can be checked using a counter. The procedure is repeated at the maximum ramp voltage and the 6500 is now in control so that any fre-

[Continued on page 86]

[From page 85] **SCALAR ANALYZER**

quency band within sweeper limits can be examined. The minimum displayed resolution is 10MHz but on broadband sweeps from F_1 to F_2 this is further limited to $(F_2-F_1)/4096$. The minimum resolution via optional GPIB interface is 4MHz.

Markers may be displayed on the screen by keyboard operation which also provides a Δ F sweep about a centre frequency. Nine front panel settings of frequency and amplitude ranges, together with any limits that have been programmed, may be recalled so giving microprocessor control of a conventional sweeper. Software allows for frequencies between 10MHz and 126GHz to be used as higher frequency detectors become available. Normal industry practice is to provide a few per cent over the frequency range so that start and stop points under external drive do not often correspond to integral values of frequencies. The 6500 caters for this by providing intelligent frequency scaling on the graticule as shown in Figure 9 where a 10 MHz to 10.39 GHz sweep shows the graticule lines at 2,4,6,8 and 10 GHz.

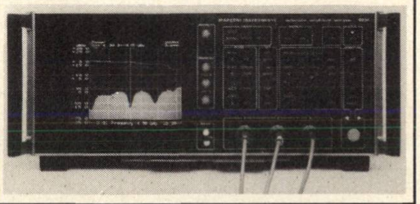


Fig. 9 6500 Front panel controls and display

Spinwheel

The need often arises in microwave measurements to closely examaine a feature in a device response curve, be it a filter, amplifier, antenna etc. The 6500 has a "brightline" cursor driven from a Spinwheel. This provides an on-screen readout of frequency and power to 10 MHz and 0.01dB resolution. The brightline control with the microprocessor form a powerful analytical tool. Response features can be examined in detail by zooming in on a brightline defined frequency range; maximum and minimum values may be instantly identified; a ΔF frequency sweep initiated for filter and amplifier analysis entered; or up to 8 on-screen markers placed at frequencies of interest. The brightline can also be coupled to the voltage Ramp by using the display FREEZE Mode. Hence the linearity of a sweeper may be checked by observing a counter output as the Spinwheel is moved and voltage ramp successively increased. Under GPIB control correction for frequency nonlinearity could be made.

Hard Copy Output

The 6500 processor and keyboard used ordinary lab X-Y recorders ro provide hard copy output so that any convenient size paper record of results may be obtained. Axes are drawn from a user defined original leaving room on the paper for alphanumeric scale information to be written by the plotter. Figure 10 shows a typical output where the 6500 has drawn axes, marked the start and stop of the frequency and marked the datum and range of the amplitude measurements. All that remains to be added by the operator are date and device type plus, of course, the QC stamp!

Developments across the whole field of electronic engineering have made possible this sophisticated accurate measurement instrument so that reliable results can be obtained at low cost in short operating times. Operator convenience of controls and on-screen graphics using modern technologies ensure the ease of use demanded by today's microwave industry.

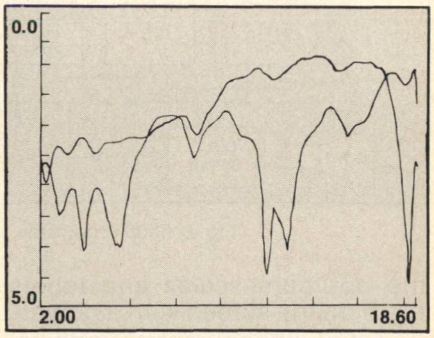


Fig. 10 Typical 6500 hard-copy output.

Acknowledgements

Thanks to Professor Cullen, and An-Tong Yi of University College London for help with the Schottky Barrier Diode characterization, and to Marconi Instruments Ltd., for permission to publish this article. ■

Microwave Network Analyzers For Millimetric Bands

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Introduction

The true network analyzer has become an indispensable tool in providing the user with the full characterization information necessary to achieve the highest performance from components and systems. For engineers working at frequencies below 18 GHz there is some choice in the range of analyzers commercially available. Above 18 GHz, there are fewer alternatives. A new automatic network analyzer system for use above 18 GHz, the MNA series, is discussed.

Background

Slotted line techniques have been and are still used as economical methods for determining, at discrete frequencies, Voltage Standing Wave Ratio and phase. The argument for "economical methods" is justifiable only if a finite number of measurements are made and the tolerance and residual characteristics of the slotted line are acceptable (e.g. for waveguide models the best attainable residual SWR at 10 GHz is of the order of 1.01 and at 100 GHz, 1.03). Further limitations are that only reflection measurements can be readily performed, repeatability is subject to operator technique and the method is laborious.

Once fuller and more complex measurement data is required, in such areas as broad band assessment, quantity production, improved repeatability or higher accuracy, a more sophisticated system is necessary. For these purposes, consideration may be given to relectometer systems, involving swept frequency techniques, where suitable equipment is available up to frequencies in excess of 100 GHz. These systems provide fast and accurate "scalar" measurements, the quality of the system being determined prinicipally by the directivity of the directional couplers used. The fundamental limitation of the reflectometer systems is that phase angle measurements cannot be made.

The facilities necessary to provide complete measurement data are found only in true microwave network analyzers. For those working at millimeter wavelengths, generally the only options available to date have been either slotted line or swept "scalar" measurements. It should be mentioned that some manufacturers have produced double down-converter systems, but these have their limitations in terms of high costs and the inherently poor performance of the coaxial line components used.

The MNA Concept

Systems incorporating 6 port network techniques have attracted wide interest in recent years. The underlying reason for that increased interest is that the vector analysis and full characterization associated with 6 port systems can now be adequately processed and easily accommodated with the use of micro-computers. The MNA design in common with other analyzer systems is based on 6 port measurement techniques[1]. Theoretically an ideal 6 port measurement network can be outlined as described below.

Taking a reference vector 'A' (unity SWR - incident wave) and a variable vector 'B' (reflected wave) with a phase difference Φ, from geometrical consideration as shown in Figure 1:

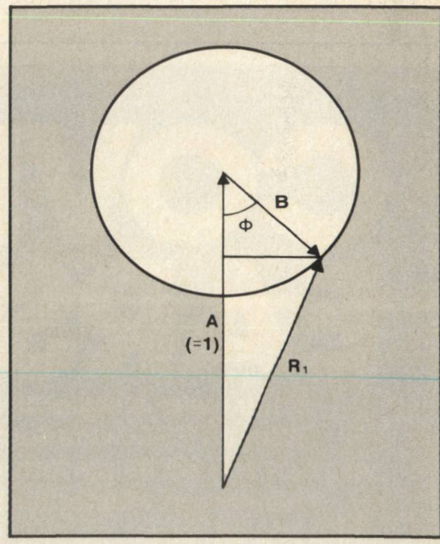

Fig. 1 Vector diagram.

$$R_1^2 = (B \sin \Phi)^2 + (1 - B \cos \Phi)^2$$

$$= B^2 \sin^2\Phi + 1 - 2B\cos\Phi + B^2\cos^2\Phi$$

$$= B^2(\sin^2\Phi + \cos^2\Phi) + 1 - 2B\cos\Phi$$

$$= B^2 + 1 - 2B\cos\Phi$$

$$2B\cos\Phi = 1 + B^2 - R_1^2$$

$$\cos\Phi = \frac{1 + B^2 - R_1^2}{2B}$$

[Continued on page 9

$$\Phi = \pm \text{ARC Cos} \frac{(1 + B^2 - R_1^2)}{2B}$$

Now B/A is the magnitude of the reflection coefficient $|\Gamma|$

The SWR is $1 + |\Gamma|/1 - |\Gamma|$ and return loss is $-20 \log_{10}|\Gamma|$

As shown in Figure 2, a directional coupler is used to measure the incident power 'A', which in this case is unity. A second high directivity coupler is used to measure the reflected power 'B'. Information for determining the resultant vector of 'A' and 'B' is derived from R_1, a probe in the line. The phase at R_1 can be translated from the probe position to the reference plane of the system. The vector measurements, unfortunately, are ambiguous because of the $\pm$ sign of the phase. To resolve the ambiguity, a phase measurement from a second probe, R_2, is required and the phase difference between the two probes has to be determined. The phase difference can be any value other than 0° or 180°, the optimum being 90°.

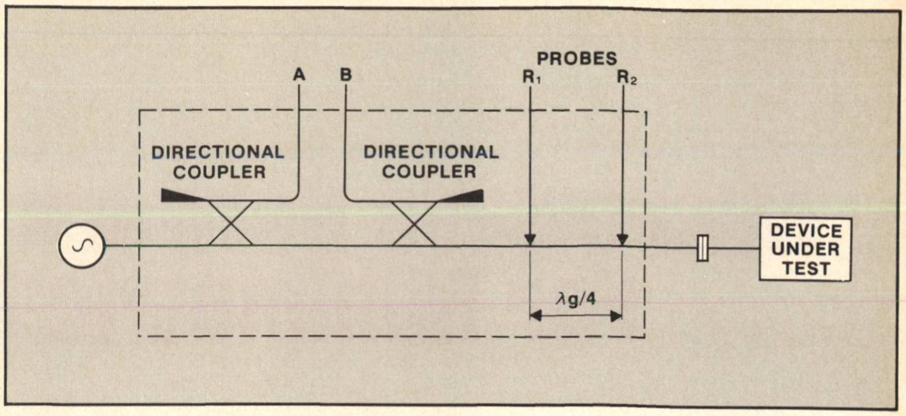

Fig. 2 Basic 6-port measurement network.

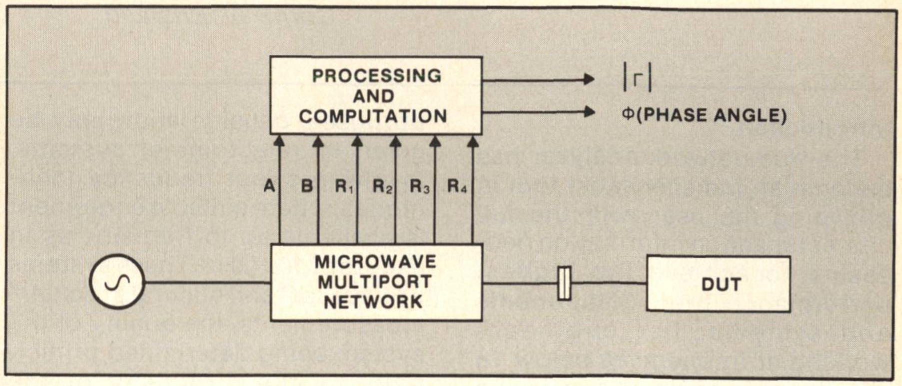

Fig. 3 Ideal 6-port network for reflection measurement.

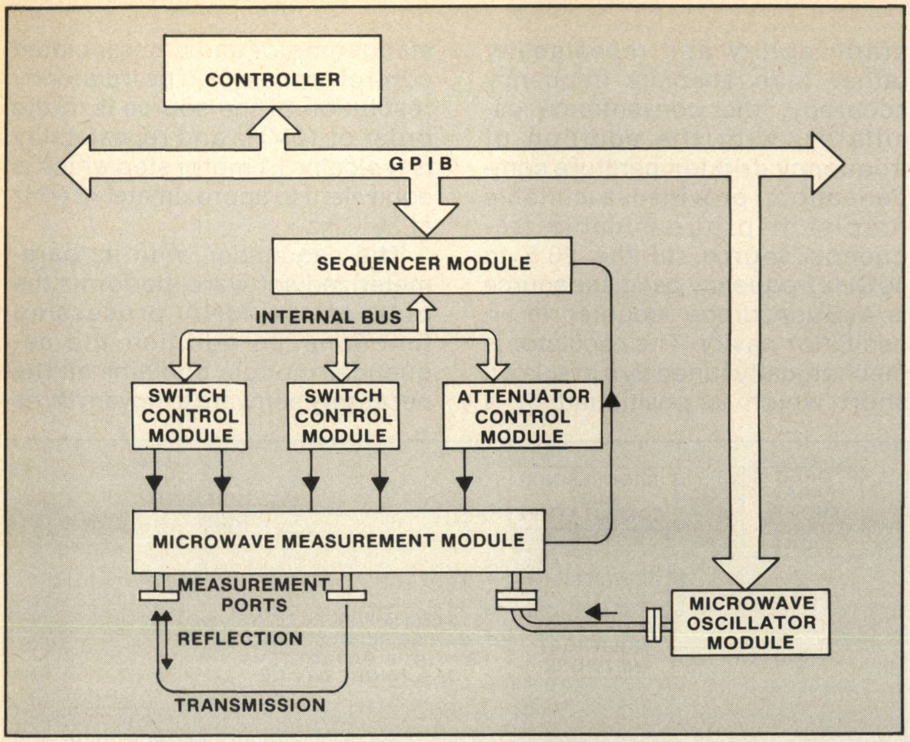

Fig. 4 MNA system diagram

A directional coupler can be substituted for the probes to combine the A and B vectors, R_1 and R_2. Thus the ideal 6 port measurement network, as shown in Figure 3, comprises:

1) An input port for signal source
2) A measuring port to connect the "device under test" (DUT)
3) A port for measuring incident signal 'A'
4) A port for measuring reflected signal 'B'
5) & 6) Two ports for measuring the vector sums 'A' and 'B' at differing phases. (For higher accuracy angular measurements additional vectors R_3 and R_4 can be sampled.)

As stated in the introductory section and further illustrated in the prinicple of 6 port coupler operation, the MNA had to be designed to be 'user friendly' due to the sheer complexity of the system concept. By the use of 'parameterized software' the operation of the MNA can be adjusted without reprogramming. When the MNA is switched on, the operator is offered a choice of types of microwave measurements which are listed, in the form of a 'menu' of "stored pre-defined set-ups" displayed on the controller VDU. The selection of a particular set-up from the 'menu' having been made, the measurement profile is then optionally displayed. The operator is now able to choose

[Continued on page 92]

either to adopt the profile as it is displayed or to modify it in order to derive a set of measurement parameters peculiar to the evaluation of the specific device under test. Once the required measurement profile is initiated, the measurement will be completed entirely without manual intervention.

The MNA System

The MNA system, as shown in Figure 4, comprises a controller, a microwave oscillator, a sequencer, several control modules and a microwave measurement module which house the 6 port network. Almost any GPIB compatible system controller may be used with the MNA, as much of the computation is executed by the sequencer module.

In selecting a source for the system, attention was given to many factors including power output, stability, frequency resolution and cost. During the period of the MNA development, synthesized sources were not readily available for all the millimeter bands. As the principle requirements for a source were programmability and repeatability rather than absolute frequency accuracy, the conventional oscillator, with the addition of frequency drift temperature compensation, provided a suitable precision programmable frequency source. In the 26.5 to 40GHz frequency band, the source is a Gunn diode mounted in an oscillator cavity. The oscillator is mechanically tuned by a precision short which is positioned by a stepper motor and it's associated control processor. The frequency resolution of the source is in the order of 10MHz and repeatability is typically ±1 motor step which is equivalent to approximately 3 MHz at 35 GHz.

The sequencer, with its parameterized software, performs the bulk of the MNA processing functions. In addition the sequencer module contains all the necessary software to govern three

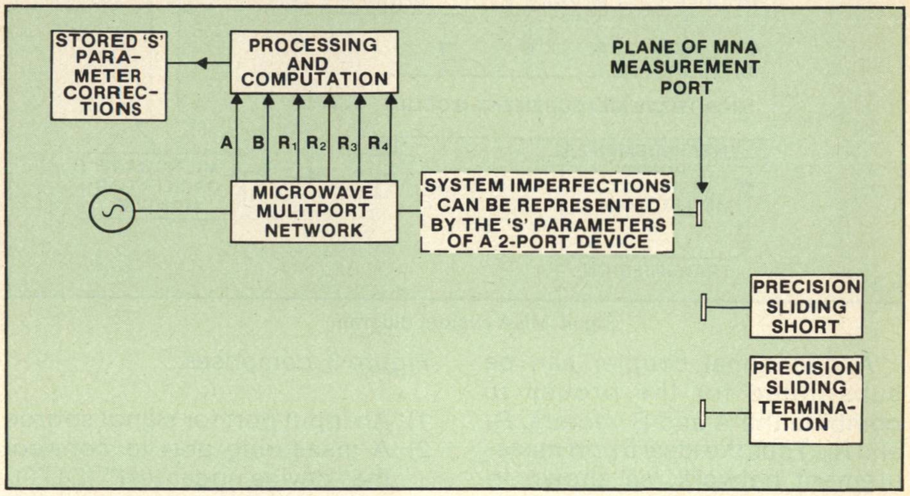

Fig. 5a MNA reflection measurement calibration (enhanced measurement.)

Date 18 Dec 81 Time is 13.28
REFECTION MEASUREMENT
Sliding Termination Set to 0 mm

F(GHz)	SWR	R/L(dB)	Phase(°)	L(mm)
29.00	1.138	23.80	+29.0	0.61
30.00	1.126	24.55	+22.3	0.43
31.00	1.116	25.20	+20.8	0.38
32.00	1.112	25.54	+14.8	0.26
33.00	1.110	25.62	+18.4	0.30
34.00	1.108	25.79	+18.1	0.28
35.00	1.101	26.37	+17.1	0.26
36.00	1.102	26.28	+11.0	0.16
37.00	1.103	26.22	+11.2	0.15
38.00	1.099	26.56	+9.6	0.13

Sliding Termination Set to 4 mm

F(GHz)	SWR	R/L(dB)	Phase(°)	L(mm)
29.00	1.133	24.12	-143.2	4.53
30.00	1.16	24.55	-130.2	4.48
31.00	1.115	25.30	-121.7	4.36
32.00	1.107	25.86	-112.4	4.28
33.00	1.108	25.82	-102.3	4.22
34.00	1.107	25.88	-90.5	4.21
35.00	1.102	26.27	-77.8	4.20
36.00	1.098	26.65	-68.5	4.16
37.00	1.102	26.26	-58.1	4.13
38.00	1.101	26.33	-46.1	4.13

Date 18 Dec 81 Time is 14.27
REFLECTION MEASUREMENT
Sliding Termination Set to 0 mm

F(GHz)	SWR	R/L(dB)	Phase(°)	L(mm)
29.00	1.138	23.79	+28.5	0.60
30.00	1.125	24.58	+21.4	0.42
31.00	1.117	25.16	+19.5	0.36
32.00	1.111	25.55	+14.9	0.26
33.00	1.111	25.60	+17.6	0.29
34.00	1.109	25.76	+16.0	0.25
35.00	1.101	26.38	+16.6	0.25
36.00	1.101	26.34	+9.5	0.14
37.00	1.105	26.07	+10.7	0.15
38.00	1.098	26.60	+8.3	0.11

Sliding Termination Set to 4 mm

F(GHz)	SWR	R/L(dB)	Phase (°)	L (mm)
29.00	1.133	24.09	-142.7	4.54
30.00	1.126	24.56	-130.5	4.48
31.00	1.115	25.30	-120.6	4.39
32.00	1.108	25.83	-112.4	4.28
33.00	1.108	25.79	-102.3	4.23
34.00	1.106	25.92	-90.6	4.21
35.00	1.101	26.39	-76.2	4.23
36.00	1.099	26.49	-68.6	4.16
37.00	1.102	26.25	-57.6	4.14
38.00	1.102	26.25	-46.9	4.12

Fig. 5b MNA reflection measurement results.

[*Continued on page 94*]

control processors, within the MNA, which interface to the 6 port microwave network.

The final section of the system, the microwave measurement module, houses the programmable reference attenuator and switches. Access to the measurement module terminals is provided in the form of three flanged wave-guide ports on the front panel. The reflection terminal is used for SWR and phase angle measurements. Both measurement ports are used to measure transmission parameters. The third port on the front panel is for the RF input signal. Because of the delicate nature of millimetric band equipment the MNA is also supplied with a component mounting platform secured to the microwave measurement module below the measurement ports. The platform and stands provide the means for positional adjustment and the secure support of components and devices under test.

Performance

One of the most important features of the MNA performance is its 'enhanced measurement' facility, see Figure 5a. By employing calibration standards at the measurement plane together with vector correction computations within the system, it is possible to 'enhance' the measurement accuracy. The effective measurement directivity of the MNA at the plane of the measurement port, using the 'enhancement' technique, is greater than 50dB. All 'calibration' and 'enhancement' data are stored on tape in the system controller during manufacture. If a user requires measurements with 'enhanced' accuracy at an alternative

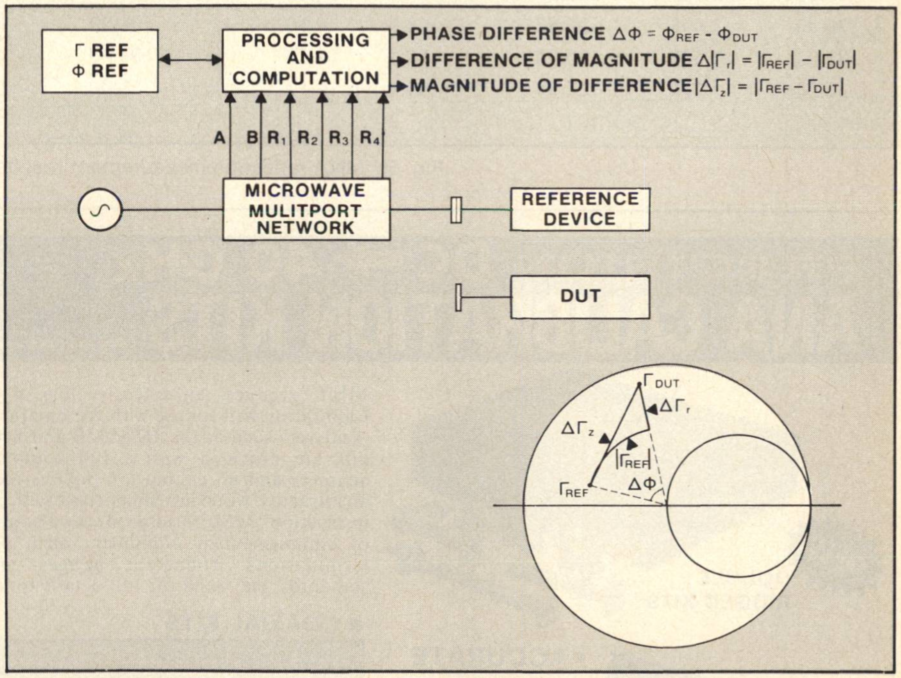

Fig. 6a MNA reflection comparator system.

F (GHz)	ΔΓz	ΔΓr	ΔΦ(°)	ΔL(mm)
29.00	.0032	-.0010	+1.7	+.04
30.00	.0032	-.0010	+1.7	+.03
31.00	.0039	-.0016	+2.0	+.04
32.00	.0043	-.0010	+2.3	+.04
33.00	.0035	-.0018	+1.7	+.03
34.00	.0034	-.0020	+1.5	+.02
35.00	.0032	-.0018	+1.5	+.02
36.00	.0035	-.0016	+1.7	+.02
37.00	.0034	-.0026	+1.2	+.02
38.00	.0041	-.0026	+1.8	+.02

Fig. 6b The comparator data for rotation of the flange of a 1.25:1 mismatch through 180° on the MNA measurement port.

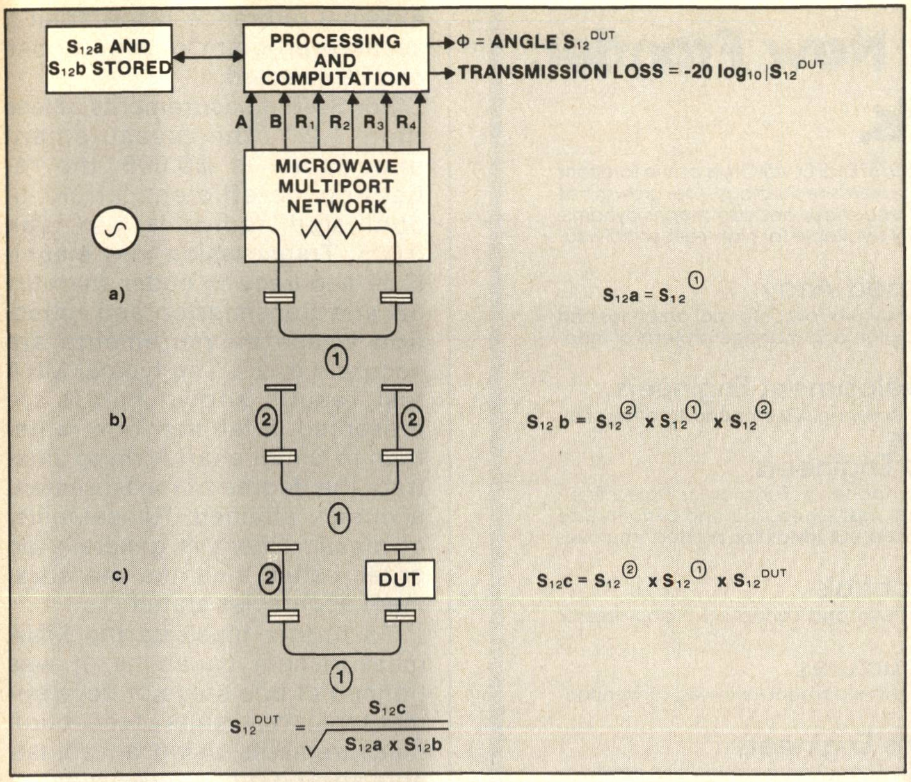

Fig. 7 MNA absolute transmission measurement system.

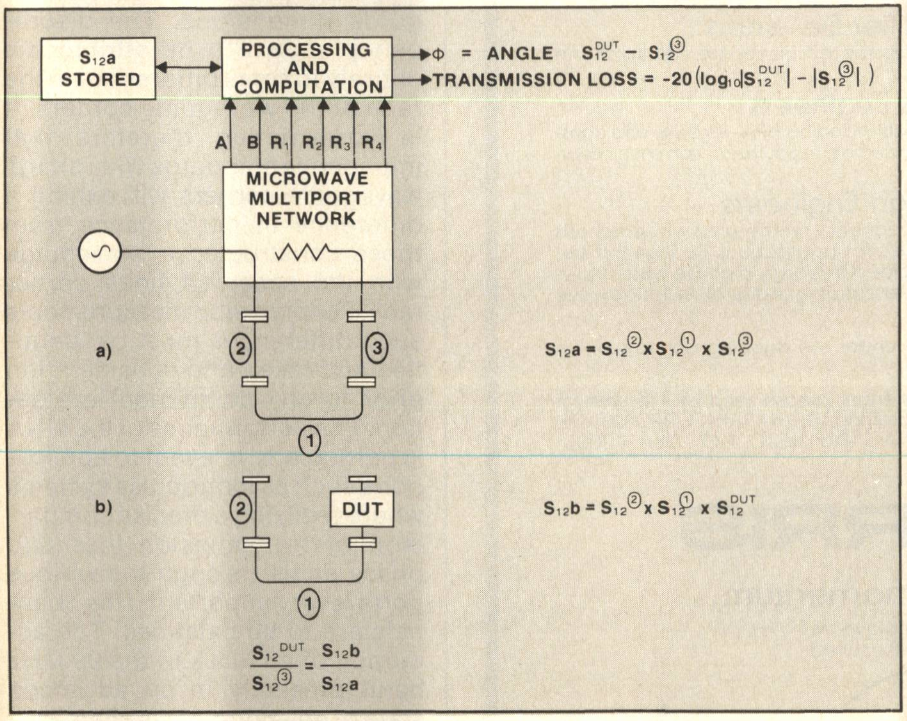

Fig. 8 MNA transmission comparator system.

TABLE I

Characteristics	MNA Model 81000-22	MNA Model 81000-27	
Frequency band	26 - 40 GHz	Centered at 90 GHz	
Phase measurements	Yes	Yes	
S Parameter measurements	Yes	Yes	
Error Correction	Applied	Applied	
Dynamic range	47dB	40dB	Provisional data
Sensitivity	-35dBm	-28dBm	Provisional data
Effective directivity	50dB	40dB	Provisional data

[*Continued on page 96*]

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external reference plane, then a separate program for this purpose can be selected.

For SWR measurements of less than 1.2:1, the measurement uncertainty is ±0.006; the reflection co-efficient 'circle of confusion' radius is less than 0.005. Transmission loss magnitude accuracy is better than 0.1 dB and transmission and reflection phase measurements are accurate to 2°. The typical MNA test results shown below are presented in tabular form rather than in Smith chart form to illustrate the degree of measurement accuracy attained. Repeatability of measurement is generally an order better than the measurement accuracies stated.

To further illustrate the MNA measurement capability, it was noticed at one stage of development that the results of reflection measurements using an adjustable short did not agree with the figures expected from the waveguide dimensions. The discrepancy shown to be attributable entirely to small differences in the radii at the waveguide corners. It is worth noting, therefore, that impedance standards with 'sharp' waveguide corners will exhibit a difference in performance from those constructed in waveguide with the accepted finite corner radii. For precision measurements such differences must be identified and taken into consideration prior to any component evaluation. The performance of the MNA is particularly relevant to applications such as monopulse systems where realizing a precise comparison of transmission loss and phase angle through the various ports is very important if the channels are to be balanced. The accuracy of an MNA in the 90 GHz band presently in an advanced state of development is compared to that of the 35 GHz system in Table I. Figure 6a illustrates the use of the MNA for reflection comparison measurements and the results of comparison measurements (Figure 6b) on a 1.25:1 mismatch rotated 180°. The absolute transmission measurement set-up is shown in Figure 7 and the transmission comparator set-up is shown in Figure 8. ■