Performance Characteristics of an Automated Broad-Band Bolometer Unit Calibration System

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Abstract—**The arbitrary six-port reflectometer concept has been applied to an automated broad-band system in the 1–18-GHz frequency range for the calibration of bolometer units. Performance evaluation results show an improvement in precision over other automated and manually operated measurement systems used at the National Bureau of Standards. Initial evaluation results reported here show a single measurement standard deviation of 0.02 to 0.41 percent from 2–18 GHz. The system is currently used for the calibration of coaxial and waveguide bolometer unit effective efficiency.**

Introduction

A BROAD-BAND measurement system has been implemented for measuring the effective efficiency of bolometer units in the 1–18-GHz frequency range using the six-port reflectometer concept and automation techniques. Although the concept was developed and demonstrated previously [1], the system described here was implemented as an operational measurement capability for microwave measurement technique development and the National Bureau of Standards (NBS) calibration services. The implementation of this microwave measurement system has demonstrated additional advantages of the six-port method. For example: 1) the six-port junction can be configured with commercial quality broad-band microwave components operating over a 1–18-GHz frequency range in a single test set; 2) RF switching is not required in critical subsystems; and 3) only one signal source is used since no intermediate frequency signals are required, thus alleviating the need for phase-locked signal sources.

Techniques were developed and incorporated into the computer program to reduce detrimental effects attributed to the thermal drift of bolometric detectors, frequency sensitivity caused by the interaction of the microwave components used in the six-port reflectometer configuration, and correction for losses in the sliding short used for the calibration of the system.

The primary function of the system is to measure the effective efficiency of coaxial and waveguide type bolometer units at closely spaced intervals ranging from 50 MHz in the 1–2-GHz frequency band to 250-MHz intervals in the 12.4–18-GHz band at power levels up to 10 mW. Typically, the estimated limits for the total error (systematic and random) of bolometer unit calibrations range from 1.0 percent in the 1–12.4-GHz range to less than 2.0 percent above 12.4 GHz. These included the uncertainty of the working standard which ranges from 0.35 percent at 2 GHz to 0.8 percent at 18 GHz. Briefly, the results presented here indicate an improvement in measurement precision of almost an order magnitude over an earlier automated bolometer unit calibration system with no apparent transfer error attributable to the measurement system.

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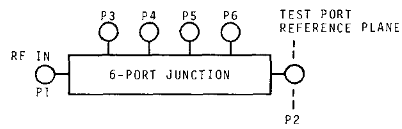

Fig. 1. An arbitrary six-port junction.

This paper briefly reviews the theory underlying the use of the six-port reflectometer technique to measure bolometer mount effective efficiency, describes the system and the measurement process, and presents the results of the system performance evaluation.

Theoretical Background

A brief review of the six-port reflectometer technique developed by Engen and Hoer [1]–[3], as it pertains to measurement of one-port device microwave parameters (specifically, bolometer unit calibration) may be in order.

Referring to Fig. 1 (a symbolic representative of a six-port junction), the real net power, P_{NET}, delivered to a load connected to the test port reference plane, $P2$, is given by

$$P_{\mathrm{NET}} = \sum q_i P_i \tag{1}$$

where P_i ($i = 3$ to 6) are the powers measured at ports $P3$, $P4$, $P5$, and $P6$, respectively. The coefficients q_i are constants determined by the properties of the six-port configuration and associated instrumentation.

A convenient, more practical form of (1) is

$$P_{\mathrm{NET}} = q_4 P_4 (p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1) \tag{2}$$

where p_3, p_5, and p_6 equal P_3/P_4, P_5/P_4, and P_6/P_4, respectively. Likewise, Q_3, Q_5, Q_6 equal q_3/q_4, q_5/q_4, and q_6/q_4.

This form does not require the use of a standard power meter during the system calibration process and allows the calibration of unknown power meters by direct substitution. Since q_4 is independent of reflections at the reference plane, the equation that provides the ratio of the net power delivered to an unknown and standard power meter, P_{NETu} and P_{NETs}, respectively, is

$$\frac{P_{\mathrm{NETu}}}{P_{\mathrm{NETs}}} = \frac{P_{4\mathrm{u}}(p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1)_{\mathrm{u}}}{P_{4\mathrm{s}}(p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1)_{\mathrm{s}}}. \tag{3}$$

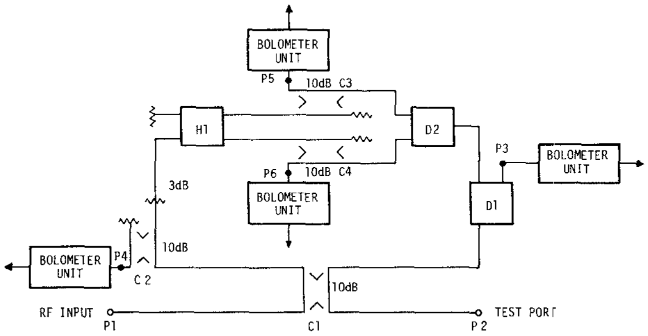

Fig. 2. Diagram of microwave measurement unit (1–18 GHz).

The constants Q_3, Q_5, and Q_6 are evaluated by measuring P_i for a minimum of three positions of a sliding short and subsequently satisfying a system of simultaneous equations in the form of (2).

The effective efficiency of a bolometer unit is defined as the ratio of the substituted dc power in the bolometer unit to the CW RF/microwave power absorbed by the bolometer unit. In the case of bolometric power meters, the effective efficiency of the unknown bolometer unit η_u is given by

$$\eta_u = \eta_s \frac{P_{bu}}{P_{bs}} \frac{P_{4s}(p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1)_s}{P_{4u}(p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1)_u}. \quad (4)$$

Measurement Unit

The measurement unit is the physical hardware subsystem which includes the microwave components of the six-port configuration and the signal amplitude detectors. Although the six-port method allows for variety in the configuration of microwave components, the specific arrangement of the measurement unit in this system is shown in Fig. 2. All components are multioctave commercially available components with a usable bandwidth of 1–18 GHz.

Port $P2$ is the test port to which the calibration and one-port device measurements are referenced. Microwave power proportional to the incident power on a load connected to $P2$ is measured at port $P4$ and the power reflected by a load at the test port is sampled at $P3$, one of the arms of the 3-dB power divider, $D1$. The combination of quadrature hybrid $H1$, power divider $D2$, and directional couplers $C3$ and $C4$ provide a complex voltage ratio measurement capability at ports $P5$ and $P6$.

Since the measurement unit was designed for the calibration of bolometer units operating in the 10-mW range, the required drive power at $P1$ is approximately 100 mW. Isolation of the signal source from signals reflected at $P2$ when highly reflecting loads are connected at $P2$ is provided by the coupling ratio of the directional coupler $C1$. The power level at $P4$ was designed to be as high as possible so that the term $q_4 P_4$ in (3) dominates the determination of P_{NET}.

System Description

Fig. 3 is a block diagram of the measurement system. Microwave power is supplied to the microwave measurement unit from the filtered and isolated output of five traveling-wave tube amplifiers. The filters attenuate the second harmonic of the fundamental frequency when the programmed frequency is in the lower half of an octave frequency band; otherwise, they are switched out of the system. The isolators provide additional protection to the traveling-wave tube amplifiers for the reason mentioned earlier. The amplifiers are driven from a sweep oscillator whose frequency and amplitude are programmed by the computer using iterative feedback. The amplitude level is continuously stabilized by analog feedback while the sweep oscillator is allowed to operate in a free-running mode. The effect of thermal drift of the bolometric detector at $P4$ is minimized by employing a thermally compensated bolometer unit at this port.

Four NBS Type II power meters [4] are used to measure the power levels at ports 3, 4, 5, and 6 while a fifth power meter is used at the test port reference plane in conjunction with standard and unknown bolometer units. Voltages representing the bolometric dc bias and substituted currents are measured at each power meter by the digital voltmeter which is switched between power meters by the computer-controlled analog scanner.

System Design Considerations

During the design of the system described above, three potential sources of error affecting the measurement accuracy and precision of the system were identified: 1) the effect of thermal drift of all bolometric detectors used within the measurement unit and the power meters (standard and unknown) connected to the test port of the unit; 2) the effect using a sliding short circuit which is not lossless; and 3) the nonideal response of the six-port configuration to frequency variations (frequency sensitivity) not attributable to the parameters being determined.

The response error was anticipated because the design goals for the measurement system included the use of commercial quality multioctave microwave components covering a frequency range from 1 to 18 GHz in a single measurement unit driven by a swept-frequency type signal generator operated in a programmed free-running mode at each nominal frequency. The most severe condition exists when a short circuit is connected to the test port and the measurement of the net power delivered to that load is attempted. Nonzero values of the net power due to frequency variations represent random errors in the determination of the system parameters, while for a given set of parameters, they are manifested as systematic errors in the measurement of microwave parameters of a device under test.

The source of this potential response error was verified experimentally by measuring the net power delivered to a short circuit connected to the test port as a function of frequency at nominally 10 GHz over approximately a 10-MHz range with 10 mW of incident power. The results showed a linear trend of 0.1 mW/MHz.

The response error itself was rendered negligible by taking two sets of power meter readings at each frequency. The first set of readings is taken with the signal source programmed

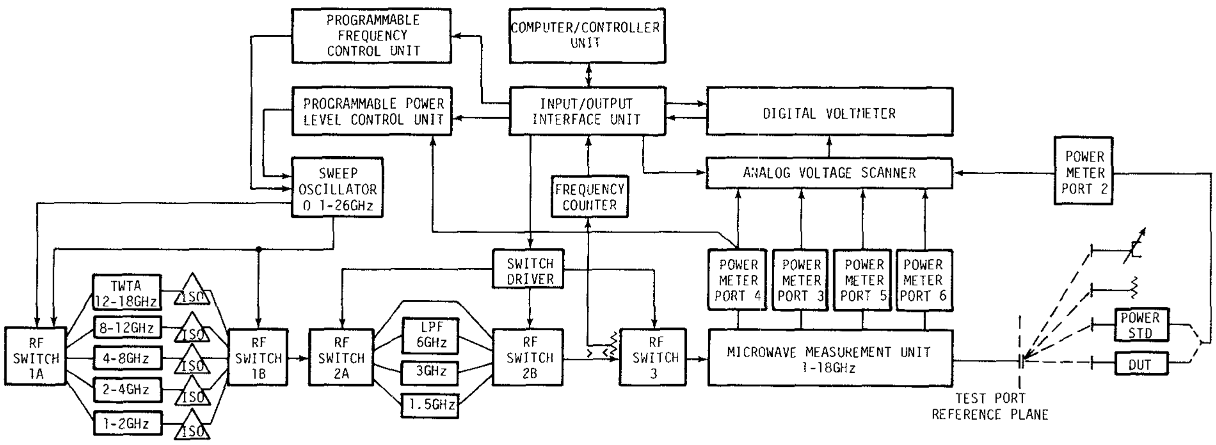

Fig. 3. Block diagram of one-port microwave parameter measurement.

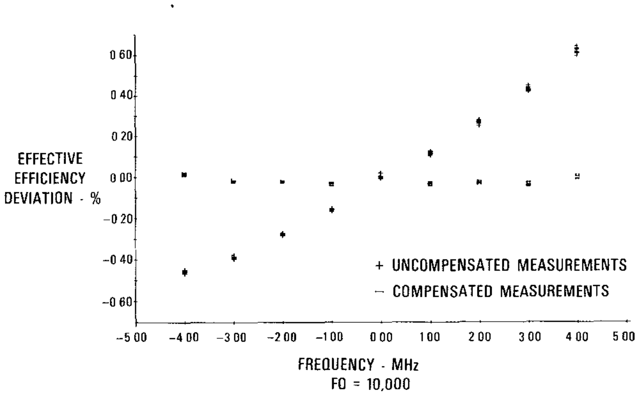

Fig. 4. Effect of frequency sensitivity on bolometer unit calibration.

approximately 0.5 MHz below the desired frequency, and the second set of readings above the desired frequency. For each power meter reading, the frequency counter provides an accurate measure of the operating frequency. Assuming that the frequency response of the measurement unit is linear over the small frequency increment, approximately 1 MHz, a "point-slope" interpolation of the power meter readings provides the required power level at the desired frequency for each of the measurement unit ports.

An experiment was conducted to illustrate the response error and the effect of the interpolation routine on the response error. The results of the experiment are shown in Fig. 4. The plot illustrates the deviation of the measured effective efficiency of a bolometer unit when the corrective interpolation routine was employed relative to the measurement results when interpolation routine was not used. The data plotted with the symbol "+" represent uncorrected measurements while the data represented by "–" are the results of the interpolation of the measurements. The vertical separation of the two plots is a measure of the measurement improvement using the frequency interpolation technique. The dispersion of the plotted points is an indication of precision of the data for ten consecutive measurements.

An alternative to eliminating this error would be the selection of a signal source, e.g., a programmable frequency synthesizer, with adequate frequency resolution and stability thus rendering the response error negligible by maintaining the operating frequency nearly constant.

The second source of error is experienced if the P_{NET} term of (3) is assumed to be zero when less than ideal conditions exist. Recognizing that a sliding short is less than ideal and not lossless over its range but assuming the loss to be a linear function of position as it is moved in uniform increments during the calibration process, the P_{NET} term is nonzero. Therefore, in developing the system of simultaneous equations for the determination of the system constants, this term must represent any microwave power dissipated in the short. Values of P_{NET} are calculated by interpolation from the slope of the relative uniformally spaced positions of the sliding short relative to a fixed short or open circuit.

The first source of error is possible because a given frequency scan of 20 frequencies requires approximately 10 min. This error was reduced to a negligible level by periodically making reference measurements of all detectors with the RF/microwave signal switched off. Using these reference measurements, the drift rate for each detector is calculated and the RF/microwave power reading corrected accordingly.

The employment of these techniques was essential for the achievement of the design goals for the overall performance of the system and their effect is responsible for the performance results presented later.

The overall system operation can be divided logically into two processes: 1) system calibration, which determines the system constants Q_3, Q_5, and Q_6; and 2) the measurement process involving the power standards and devices under test.

System Calibration Process

Earlier it was mentioned that the calibration of the six-port junction for power measurement requires a minimum of three offset shorts or sliding load positions, and a power standard. These minimum requirements have been augmented and slightly modified to accommodate practical considerations in the system operation. Specifically, 1) eight sliding short positions and a fixed short or open circuit are used during the calibration procedure, and 2) the power standard is deferred to the measurement procedure discussed later.

The use of more than the minimum sliding short positions provides advantages such as measurement redundancy in calibration process which provides an estimate for precision of the sliding short data and also provides a distribution of points in the complex plane as the phase of the short is changed, thereby improving the resolution of the system constants. The latter is particularly important since the measurement system is designed to operate over an octave bandwidth on a given measurement occasion.

Bolometer Unit Measurement Process

The bolometer unit measurement process is a sequence of measurements made on both working standards and bolometer unit being calibrated. The order of the measurements is unspecified but limited to ten devices and a total of 32 measurements in a given measurement session. The number of measurements for a given system calibration is limited by the stability of the measurement unit. Although this limit has not been completely determined valid, bolometer unit measurements have been made over several days using a single system calibration.

In practice, three working standards and a number of unknown bolometer units are connected to the test port of the measurement unit four times. The measurement data are then processed to provide the effective efficiency of unknown devices and the working standards which are also treated as unknowns in this phase of the process. For each unknown device, working standards included, the effective efficiency is determined by pooling the measurements of the working standards and the measurement of the unknown device. Thus the effective efficiency of an unknown bolometer unit is determined by 12 standard measurements and 4 devices under test measurements.

The treatment of the working standards as unknown devices provides data for maintaining the integrity of the measurements for each measurement occasion as well as long-term control occasion-to-occasion control charts.

Fig. 5 is a tabulation of a typical set of bolometer unit calibration results. The estimated limits of uncertainty are the sum of the systematic uncertainty limit (estimated at 99-percent engineering confidence) of the working standard and the random error limit of the calibration process. The random error limit is the square root of the sum of the squares of the 99-percent confidence intervals for the effective efficiency of the standard and that of the device under test.

System Performance Evaluation

The usual approach to measurement error evaluation is to separate the measurement system into its critical subsystems, evaluate the potential for systematic error in each (theoretically or experimentally), and by application of error propagation procedures determine the effect on the final measurement result. However, with a system as complex as described above, this approach was determined to be impractical. Since this system's primary measurement function is to measure an unknown bolometer unit relative to a standard bolometer unit, a more direct approach, described in a previous paper [5], for the evaluation of both systematic and random errors was chosen.

Frequency MHz	Power mW	Refl Coef +-.005	Effective Efficiency	Computed Standard Deviation	Estimated Limits of Uncertainty percent
8000	10	0.000	0.9733	0.0002	1.00
8200	10	0.000	0.9729	0.0001	1.00
8400	10	0.000	0.9724	0.0000	1.00
8600	10	0.000	0.9720	0.0001	1.00
8800	10	0.000	0.9716	0.0002	1.00
9000	10	0.000	0.9712	0.0001	1.00
9200	10	0.000	0.9709	0.0001	1.00
9400	10	0.000	0.9704	0.0003	1.00
9600	10	0.000	0.9702	0.0003	1.00
9800	10	0.000	0.9701	0.0005	1.00
10000	10	0.000	0.9697	0.0006	1.00
10200	10	0.000	0.9694	0.0006	1.00
10400	10	0.000	0.9689	0.0006	1.00
10600	10	0.000	0.9683	0.0005	1.00
10800	10	0.000	0.9680	0.0006	1.00
11000	10	0.000	0.9677	0.0004	1.00
11200	10	0.000	0.9682	0.0004	1.00
11400	10	0.000	0.9677	0.0002	1.00
11600	10	0.000	0.9673	0.0003	1.00
11800	10	0.000	0.9655	0.0005	1.00
12000	10	0.000	0.9628	0.0007	1.00
12200	10	0.000	0.9620	0.0005	1.00
12400	10	0.000	0.9638	0.0004	1.00

Degrees of Freedom for computed Effective Efficiency: 4

Fig. 5. Typical bolometer unit calibration printout.

The model for this measurement of the ratio of two unknown effective efficiencies is

$$\frac{\eta_u}{\eta_s} = \frac{P_{bu}}{P_{bs}} \frac{P_{4s}(p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1)_s}{P_{4u}(p_3 Q_3 + p_5 Q_5 + p_6 Q_6 + 1)_u}. \tag{5}$$

This model is useful because the basic measurement made by the system is the ratio of effective efficiencies of two bolometer units described by (4). In practice, η_s the effective efficiency of the working standard is known as a result of previous evaluation relating to a National Bureau of Standards reference.

As in [5], the same particular systematic error was evaluated for comparison purposes and to establish its effect, if any, on the system's measurement result. This error is "caused by the measurement system only and not the working standard or the unknown bolometer units." The model for this evaluation is the product of inverse ratios of η_s/η_u and η_u/η_s given by

$$yy' = 1 + \left(\frac{\eta_s}{\eta_u} + \frac{\eta_u}{\eta_s}\right)\Delta + \Delta^2 + e \simeq 1 + 2\Delta + e \tag{6}$$

where e is a random error term, and the presence of a nonzero Δ is determinable by the measurement of η_s/η_u and η_u/η_s ratios.

Random measurement errors are attributable to short-term sources of variance such as connector low repeatability and instabilities in system components for a given calibration of system constants, while occasion-to-occasion errors are attributable to system setup and variability in the system calibration. The latter sources of measurement error, although variable on a long-term basis, are systematic in effect on the measured value of an unknown bolometer unit. The random error standard deviation reported in this paper represents the short-term random variations only. Data for

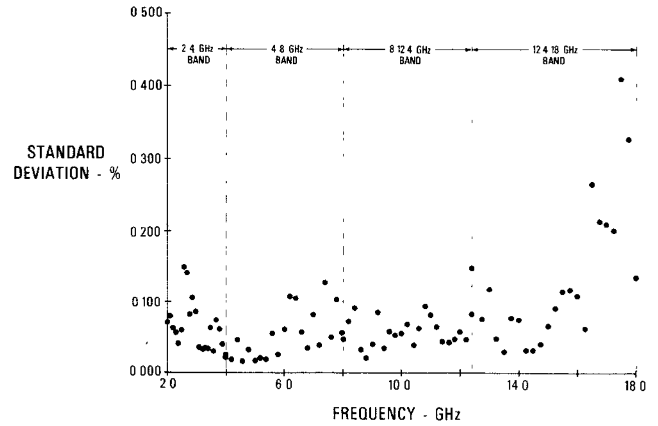

Fig. 6. Standard deviation for a single measurement.

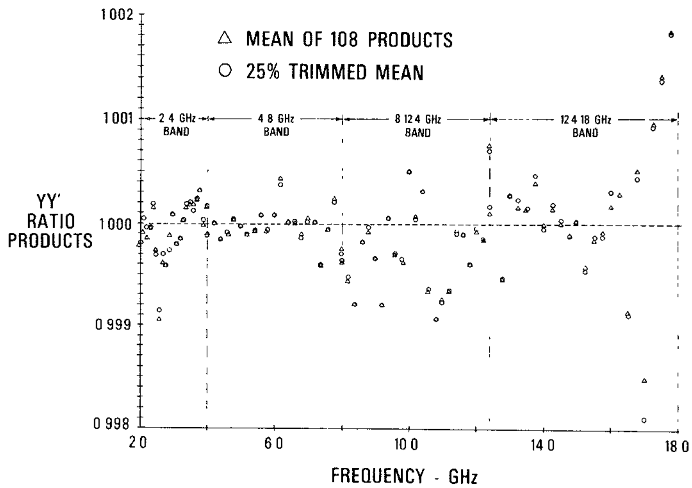

Fig. 7. Plots of mean and 25-percent trimmed mean of 108 products of pairs of inverse ratios.

the determination of the latter source of error are being collected but, however, do not enter into the evaluation presented here.

Ratio Experiment Design

An abreviated version of the ratio experiment described in [5] was implemented. The experiment was conducted with three bolometer units with type-N connectors. These represent typical devices normally measured on the system. Measurements were made on a single occasion on four of the five frequency bands at which the system normally operates, 2–4, 4–8, 8–12.4, and 12.4–18 GHz. Although the experiment design lacked the advantage of multiple occasion calibrations at each band, a comparison of the single calibration on a band-to-band basis served the same purpose for detecting first-ordered effects due to the variability of the system calibration. For the measurement occasion at each band, the three bolometer units were connected in sequence four times. In each band, multiple frequency measurements were made at intervals of 100 MHz from 2 to 4 GHz, 200 MHz, 4 to 12.4 GHz and 250 MHz, 12.4 to 18 GHz. Thus from the measurement of three bolometer units, four times at each frequency, 108 independent ratio products were developed.

Data Analysis

The measurements of the three bolometer units were combined to make the estimate of the standard deviation of single frequency. These are shown in Fig. 6. Although the data represent a single measurement at each frequency band, there appears to be no evidence of frequency-band dependent effects. The standard deviation of a single measurement ranges from 0.02 to 0.15 percent from 2 GHz to 16 GHz increasing to 0.41 percent at 17.25 GHz.

The total random error standard deviation of a single measurement reported in the earlier paper [5] ranged from 0.2 to 1 percent in the 2- to 12.4-GHz frequency range. By way of comparison over the same frequency range, the random error ranges from 0.02 to 0.15 percent, an improvement of almost ten to one.

Plots of the mean and 25-percent trimmed mean of the 108 products of pairs of inverse ratio measurements YY' at each frequency are shown in Fig. 7. Although random errors are present, the average of the set of 108 ratio product should not be (statistically) significantly different from 1.0. The data appear to be distributed uniformally about 1.0 with no detectable evidence of the type of systematic error described earlier.

The 25-percent trimmed mean is computed by ignoring the 25-percent largest and smallest product ratio values and averaging the middle 50 percent. This technique exposes the effect of measurement "outliers." When, as in this case, the trimmed mean and usual or average mean tend to be close, outliers are not present.

As mentioned earlier, each frequency band can be considered a separate system since independent system calibrations are required prior to bolometer unit measurement. The plot of YY' ratio products do not reveal any significant evidence of band-to-band or occasion-to-occasion as a function variability which would have been displayed as systematic offset of the plotted data for one or more of the frequency bands.

Furthermore, it appears that in the course of calibrating typical bolometer units, if any systematic error exists it is not significant in comparison to random errors (0.02 to 0.41 percent) and uncertainty in the working standards which range from 0.35 percent at 2 GHz to 0.8 percent at 18 GHz.

Conclusion

A broad-band measurement system has been developed for the calibration of bolometer units in the 1–18-GHz frequency range using the six-port reflectometer technique. The six-port reflectometer was configured using a multi-octave broad-band device to cover the whole frequency range in a single measurement unit.

Techniques were developed to reduce the detrimental effects of bolometer unit thermal drift, the dissipative losses in the sliding short used in the system calibration process, frequency sensitivity of the measurement unit, and signal source instability.

The preliminary evaluation shows the total random error standard deviation of a measurement range from 0.02 to 0.41 percent over the 2–18-GHz frequency range. Also, it has been determined experimentally that one type of systematic error can be neglected.

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Short Papers

A Cost-Effective Modular Downconverter for *S*-Band WEFAX Reception

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Abstract—**The relocation of weather satellite facsimile downlinks from VHF into *S*-band has generated a requirement for reliable, low-cost microwave receiving equipment. This paper explores many of the design tradeoffs encountered in developing one such receiver system.**

INTRODUCTION TO WEFAX

For the past decade, meteorological agencies around the world have received periodic weather facsimile (WEFAX) and automatic picture transmission (APT) printouts from a network of polar orbiting and geosynchronous satellites [1], [2]. The products available from these satellites are diverse, but generally include computer-gridded cloud cover maps such as the one shown in Fig. 1, derived from satellite-borne optical and infrared sensors [3]. Ground reception of such signals supports not only weather prediction, but also geological resource assessment and agricultural planning activities.

WEFAX coverage is currently limited to the western hemisphere, while APT is a worldwide, direct broadcast service. Users depending upon these transmissions include underdeveloped nations operating their ground receiving stations on an extremely limited budget and under the most adverse environmental conditions. The challenge facing the designer of WEFAX and APT receiving equipment thus involves assuring the utmost in reliability, ease of operation by unskilled personnel, and of course absolute minimum cost.

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FREQUENCY ALLOCATIONS

Several generations of weather satellites have transmitted frequency-modulated downlink signals in the 135–138 MHz region. A degree of standardization has begun to emerge with regard to image formatting, enabling users to recover multiple satellite products on a single receiver and display device, with minimum equipment modification. Perhaps a thousand commercial VHF weather satellite receiving stations now exist worldwide. Countless other, less elaborate systems have been fabricated by individual hobbyists and experimenters [4].

Spectrum allocation requirements, as well as a desire to escape ionospheric propagation anomalies, have dictated the assignment of downlink frequencies in the microwave region for the latest series of meteorological satellites. The first two of these Designated Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite (SMS/GOES), have been deployed by the U.S. National Oceanic and Atmospheric Administration (NOAA). They have recently been joined in geostationary orbit by GMS, the Japanese weather satellite, and will be supplemented shortly by two additional geostationary satellites now being developed by the USSR and the European Space Agency (ESA). The five spacecraft will be positioned above the equator approximately seventy degrees apart, thus providing nearly global WEFAX coverage.

All of these satellites will transmit WEFAX at a frequency near 1.7 GHz, with modulation characteristics and image format being fully compatible with present VHF WEFAX transmissions. In order to assure maximum utilization of existing equipment, linear downconversion has emerged as an accepted technique for developing worldwide *S*-band WEFAX receiving capability.