AN APPLICATION OF THE POWER EQUATION CONCEPT AND AUTOMATION TECHNIQUES TO PRECISION BOLOMETER UNIT CALIBRATION

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Abstract

The power equation concept has been implemented into a multioctave precision bolometer unit calibration system employing automation techniques in conjunction with an automatic network analyzer system. The system was qualified as a calibration transfer system operating in the 2-12.4 GHz frequency range at 1 to 10 mW with a single measurement standard deviation of 0.2% to 1% from 2-10 GHz.

Introduction

The need for multiple frequency calibration services has been served by the combination of the power equation concept with an Automated Network Analyzer (ANA) in the development of a multioctave bolometer unit calibration system. The system is capable of measuring the effective efficiency of coaxial and waveguide type bolometer units at 100 MHz intervals in the 2-12.4 GHz frequency range at power levels of 1 to 10 mW.

The core of the system is an optimal configuration of broadband directional couplers into a 4-port network (see Fig. 1) which enables the use of power equation concepts to describe the transfer of rf power between a source and a load. The ANA facilitates the measurement of complex voltage ratios which are required for the evaluation of mismatch factors and terms which are related to the 4-port network and the ANA measurement system.

Techniques were developed for the calibration of the system over its entire frequency range consistent with the requirements of a precision measuring system.

Statistical methods were applied in the initial evaluation of systematic and random sources of error, and for the collection of control chart data.

Theoretical Background

The development of power equation concepts [1] and subsequent efforts of others [2,3] leads to an expression, in terms of measurable quantities, for determining the effective efficiency, η_u, of an "unknown" bolometer unit relative to a working standard having an effective efficiency η_s:

$$\eta_u = \eta_s \frac{P_{bu}}{P_{bs}} \frac{M_{gs}}{M_{gu}} \qquad (1)$$

where P_{bs} and P_{bu} are respectively the bolometrically substituted dc powers in the working standard and unknown bolometer units, and M_{gs} and M_{gu} are the mismatch factors between the rf source and the respective loads.

The latter can be evaluated by:

$$M_{g\ell} = 1 - \frac{|W_\ell - R_c|^2}{R^2} \qquad (2)$$

where R and R_c are properties of the 4-port network and the measuring system and W_ℓ represents the response of the measurement system with the load connected to the 4-port.

Instrumentation

The configuration, Fig. 1, of multi-octave directional couplers allows the measurement of the complex voltage ratio, b_3/b_4 which is needed for the evaluation of R, R_c and W_ℓ. The power measurement at P_4 accounts for variations in power level during various phases in the overall measurement process. The line stretcher facilitates adjustment of the reference and signal transmission lines to equal physical and electrical length and also provides a sliding short function during the calibration process.

The block diagram shown in Fig. 2 represents the complete system including the auxiliary instrumentation, e.g., the pre-bias and switching unit which facilitates the handling of a number of bolometer units without appreciable loss of time.

Calibration and Measurement Process

Calibration of the system is accomplished in two phases, the evaluation of R, R_c, and the measurement of rf power at the test port, P_2, relative to the power at P_4 using a previously calibrated working standard. The latter is quite straight forward, however the evaluation of R and R_c required the development of an appropriate technique.

With a short circuit connected to the test port, and as the line stretcher position is changed, the complex ratio b_3/b_4 describes a circle in the complex plane, not necessarily centered at the origin, having radius R and center R_c. At each programmed frequency the network analyzer measures b_3/b_4 for each position of the line stretcher. The computer program has been designed to accomodate up to 15 measurements, and to least square fit the data to a circle and determine its radius and center. These data are stored for later determination of M_{gs} and M_{gu}. Tests are included in the computer program to assure the operator of a valid calibration. Fig. 3 is a typical print out of the circle fitting results.

The system calibration process is completed with the evaluation of M_{gs} and system factor,

$$K_A = \left[\eta_s \frac{P_{b4s}}{P_{bs}} M_{gs}\right]^{-1} \qquad (3)$$

where P_{b4s} represents the bolometrically substituted dc power at P_4 of the 4-port network with working standard connected to the test port, with M_{gs} evaluated by (2).

The determination of effective efficiency of a bolometer unit is completed with the substitution of the working standard for the unknown and the measurement and evaluation of P_{b4u}, P_{bu}, and M_{gu} and combined with K_A as

$$\eta_u = \frac{P_{bu}}{P_{b4u}} \frac{1}{M_{gu}} \frac{1}{K_A}$$

$$= \eta_s \frac{P_{bu}}{P_{bs}} \frac{M_{gs}}{M_{gu}} \frac{P_{b4s}}{P_{b4u}} \qquad (4)$$

where P_{b4u} represents the bolometrically substituted dc power at P_4, and the ratio P_{b4s}/P_{b4u} serves to account for power variation during the bolometer unit substitution process. Fig. 4 illustrates typical printouts of the measurement results.

Measurement Error Evaluation

Four sources of systematic error associated with the calibration transfer system are:

1) Error in effective efficiency, η_s, of the working standard. (This error is not related to the transfer system since its value is determined independently but does impact the final results.)
2) Bias due to the ANA only and not the working standard or unknown bolometer units.
3) Bias due to an interaction between the ANA and the working standard.
4) Bias due to the interaction between the ANA and the unknown bolometer unit being measured.

Random errors associated with the measurement process include connector repeatability, within occasion and occasion to occasion precision.

Two experiments were designed which allowed a statistical evaluation of these errors, one to evaluate the calibration test set attached to the ANA and the second to simulate normal operation for the purpose of evaluating random error components of the measurement process and obtaining initial data for control chart and quality control procedures.

A partial summary of the error evaluation results are illustrated in Fig. 5 and 6. Fig. 5 shows a plot of the effective efficiencies, η_E/η_A, of a pair of bolometer units of different model types. The pair of lines at the bottom of the figure show the width of 95% confidence interval for the true ratio at that frequency. Amplitude variation in the ratio curve equal to the width of the confidence interval can be attributed to random error while larger variations are probably real.

Fig. 6 shows an estimate of the standard deviation of a single measurement. It contains the effect of both within and between occasion random error. The dots indicate the effect of eliminating "bad occasions" from the data.

The standard deviation ranged from .2% at 2 GHz to 1% at 12 GHz except between 11 and 11.7 GHz. The increase in standard deviation at higher frequencies is believed to be caused by a nonrepeatable loss associated with the type N coaxial connectors used on the bolometer units. More definitive experiments will be used to isolate the source of this random error in the near future.

Systematic errors averaged +.02% with bound to +.04% in the 2-10 GHz frequency range, above 10 GHz the same positive error was evident but poorer precision made an exact determination impossible.

Conclusions

The power equation concept and the automatic techniques were implemented into an automated bolometer unit calibration system in the frequency range of 2-12.4 GHz at 1-10 mW power level. The evaluated systematic and random errors over the frequency range qualify the system as a precision calibration transfer system although new techniques will need to be developed to reduce the effect of random errors from 10-12.4 GHz.

Acknowledgments

The technical guidance and assistance of Dr. G.F. Engen is gratefully acknowledged. Manly P. Weidman provided the computer programs for the system control and measurement process, Peter V. Tryon and his staff designed statistical evaluation experiments, analyzed and evaluated the results, Gary L. Rosenberger assisted with the data collection and processing, all their efforts are greatly appreciated.

References

[1] G.F. Engen, "An Introduction to the Evaluation of Microwave Systems Using Terminal Invariant Parameters," U.S. Dept. Comm., Nat. Bur. Stand., NBS Mono. 112, Oct. 1969.
[2] F.R. Hume, F.K. Koide, and D.J. Dederich, "Practical and Precise Means of Microwave Power Meter Calibration Transfer," IEEE Trans. Instrum. Meas., Vol. IM-21, pp. 457-466,Nov.1972.
[3] G.F. Engen, "Theory of UHF and Microwave Measurement Using the Power Equation Concept," U.S. Dept. Comm., Nat.Bur.Stand., NBS Tech. Note 637, Apr. 1973.

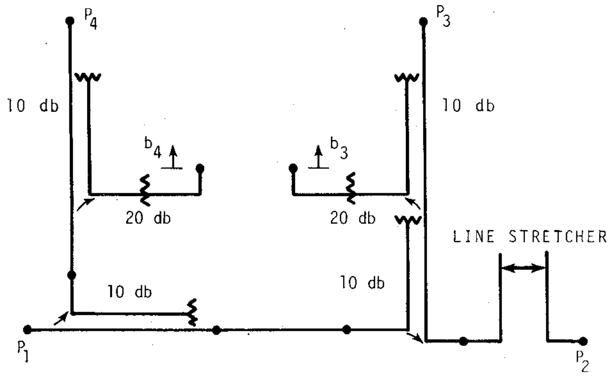

Fig. 1. 4-Port coupler.

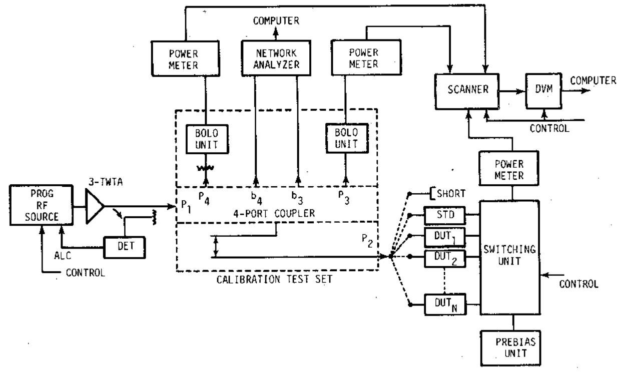

Fig. 2. Calibration system block diagram.

FREQUENCY	AREA	RADIUS	XCEN	YCEN	RESIDUAL
4000	.87	2.5634	.149034	.015004	-.24E-01
					-.32E-02
					.720E-02
					-.22E-01
					.128E-01
					-.74E-03
					.208E-01
					-.10E-01
					.594E-02
					.127E-01
					.552E+00%
4200.	.86	2.5541	-.04450	-.07868	-.19E-01
					-.29E-02
					.465E-02
					-.15E-01
					.840E-02
					.156E-02
					.197E-01
					-.14E-01
					.968E-02
					.676E-02
					.467E+00%
4400.	.93	2.5178	.028729	.054846	-.12E-01
					-.14E-01
					.320E-02
					-.13E-01
					.806E-02
					-.14E-02
					.218E-01
					-.19E-01
					.167E-01
					.945E-02
					.532E+00%

Fig. 3. Typical system calibration printout.

a)

STD. NO.-- 2209 ID--STANDARD

FREQUENCY	KA	MGL	PMAIN	PSIDE
4000.	1.60880	.98850	7.4225	4.7452
4200.	1.58169	.99565	7.4782	4.8298
4400.	1.56509	.99663	8.1854	5.3428
4600.	1.56504	.99752	8.8999	5.8077
4800.	1.54991	.99253	8.0690	5.3474
5000.	1.53589	.99905	7.4391	4.9456
5200.	1.51527	.99352	7.6209	5.1671
5400.	1.50310	.99888	8.6738	5.8998
5600.	1.49137	.99968	9.9281	6.8034
5800.	1.48588	.98945	10.6779	7.4210
6000.	1.47306	.98748	10.3040	7.2378
6200.	1.46112	.99882	9.5631	6.6982
6400.	1.44296	.98482	8.9367	6.4315
6600.	1.43368	.98258	8.5117	6.1832
6800.	1.42116	.99233	9.1453	6.6395
7000.	1.40597	.99829	10.0577	7.3398
7200.	1.40447	.99391	10.0488	7.3757
7400.	1.39804	.99747	9.5528	7.0194
7600.	1.38257	.99813	8.5324	6.3369
7800.	1.39110	.97929	7.5258	5.6620
8000.	1.39554	.99136	7.3931	5.4769

b)

UNKNOWN NO.-- 2280 ID--UNKNOWN

FREQUENCY	EFFICIENCY	MGL
4000.	.97914	.98938
4200.	.97905	.99504
4400.	.97874	.99712
4600.	.97851	.99792
4800.	.97813	.99345
5000.	.97798	.99928
5200.	.97778	.99438
5400.	.97691	.99882
5600.	.97654	.99944
5800.	.97571	.99090
6000.	.97614	.98741
6200.	.97568	.99916
6400.	.97517	.98528
6600.	.97479	.98231
6800.	.97447	.99332
7000.	.97366	.99783
7200.	.97362	.99379
7400.	.97359	.99692
7600.	.97342	.99834
7800.	.97360	.97792
8000.	.97373	.99124

Fig. 4. a) Typical test port calibration.
b) Typical bolometer unit calibration.

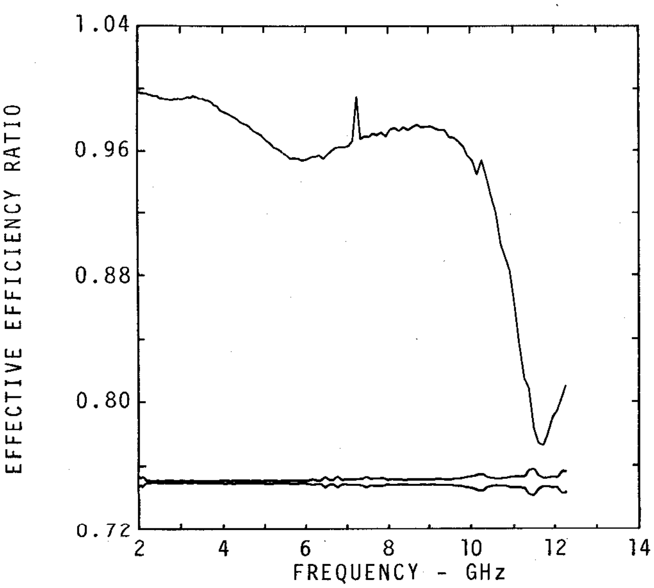

Fig. 5. Effective efficiency ratio of two bolometer units.

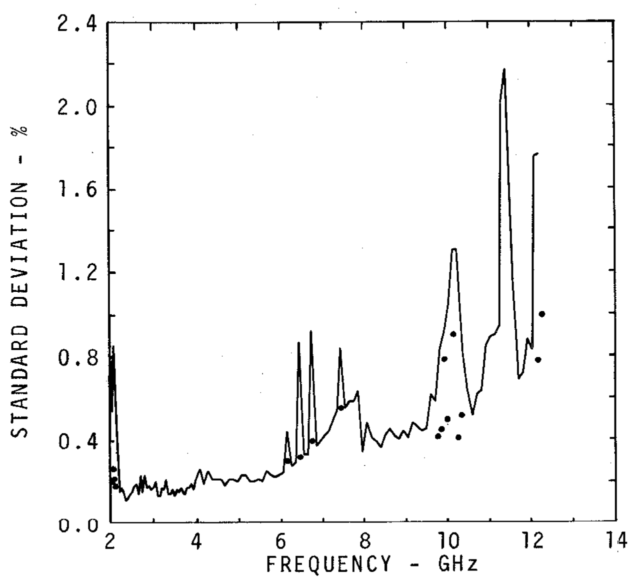

Fig. 6. Standard deviation of a single measurement.