MEASUREMENT SERVICE FOR HIGH-POWER CW WATTMETERS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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Abstract

In response to recent interest and demand for accurate high-power calibrations, the National Institute of Standards and Technology has established a measurement service for high-power continuous wave (cw) wattmeters. The automated calibration system operates at power levels of 1 to 1000 W for frequencies from 1 to 30 MHz and 1 to 500 W for 30 to 400 MHz. The high-power source is calibrated using a transfer standard, which was calibrated using a cascaded coupler technique that is traceable to a 10 mW standard. Wattmeters are calibrated directly against the high-power source and must meet the following specifications: an IEEE-488 interface bus, a type N male input connector, and either a type N female output connector or an attached load. At each measurement point the calibration factor is defined as the ratio of the wattmeter's indication to the power incident on it. Systematic uncertainties are due to the high-power source calibration factors, instability of the source, resolution of the wattmeter, and reflection coefficient measurements. Random uncertainties are due to connector repeatability of the devices, environmental effects, long term system variations and system noise. The measurement uncertainty is less than plus or minus two percent and is dependent on the frequency and power level.

1. Introduction

NIST has previously established a measurement capability to support high-power wattmeters employing the cascaded coupler technique [1]. This method extends power measurements to high levels that are traceable to a 10 mW standard thermistor mount. An arrangement of nominal 10, 20, 30, 40, and 50 dB couplers with side-arm power meters is required for measurements up to 1000 W. The initial step transfers the calibration of the 10 mW standard to the 10 dB coupler/power meter. The standard is then replaced with a wattmeter to be calibrated. RF power is increased 10 dB and the calibration is transferred to the adjacent 20 dB coupler/power meter. This sequence is repeated with the remaining coupler/power meters until the wattmeter is calibrated at the desired power levels and frequencies. Power ratios calculated from simultaneous power measurements made at each transfer are used to calculate the incident power at the wattmeter.

Once the wattmeter was calibrated, it

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was used to calibrate a high-power source. Secondary wattmeters may now be calibrated directly against the source. This reduces the measurement time and the number of required connections; the drawback being an additional level in the calibration structure which results in higher uncertainties.

2. System Description

The high-power source provides a stable rf signal at power levels of 1 to 1000 W for frequencies from 1 to 30 MHz, and 1 to 500 W from 30 to 400 MHz [2]. The frequency and output power are controlled by software. A closed-loop feedback arrangement maintains the output power within ±0.005 dB. The rf power path is switched to one of three output ports depending on frequency.

Measurements have been performed on two commercial wattmeters that measure rf power directly using diode power sensors. These sensors, used in conjunction with a meter as a display, are microprocessor-based. Each sensor carries its own wideband calibration constants in self-contained nonvolatile memory. Since the calibration data are stored in the sensor, any sensor may be used with any meter. Each wattmeter has one sensor, denoted Sensor 1, that measures powers between 0.3 and 1000 W for frequencies between 1.8 and 32 MHz, and another, Sensor 2, that measures powers between 0.3 and 1000 W for frequencies between 25 and 1000 MHz. Sensor 1 is used at frequencies between 2 and 30 MHz and Sensor 2 is used at frequencies between 30 and 400 MHz.

Of the two wattmeters used, Wattmeter 1 was initially calibrated using the cascaded coupler technique. It was, in turn, used to calibrate the high-power source, and hence may be referred to as a transfer standard. Wattmeter 2 was also calibrated using the cascaded coupler technique for comparison purposes. Both wattmeters were calibrated with the high-power source, and their calibration factors were compared against those obtained using the cascaded coupler technique. The results will be presented in a later section.

Any commercial wattmeter may be used in the system, as long as it can be accessed via an IEEE-488 bus, has a type N male input connector, and has either a terminating high power load or a type N female output connector that may be connected to the high-power load at NIST.

The computer controls the rf source and handles the data acquisition and processing through an IEEE-488 bus.

3. Measurement Methods

An unknown wattmeter may be calibrated by connecting the transfer standard and the unknown wattmeter in succession to the output port of the high-power source. Desch and Larson [3] have shown that the microwave power incident on the unknown wattmeter under calibration, P_X, is

$$P_X = P_{TS} \frac{P_{CX}}{P_{CT}} \frac{|1 - \Gamma_G \Gamma_{TS}|^2}{|1 - \Gamma_G \Gamma_X|^2}, \qquad (1)$$

where P_{TS} is the power incident on the transfer standard, P_{CT} is the power read by the high-power source with the transfer standard connected to its output port, P_{CX} is the power read by the high-power source with the unknown wattmeter connected to its output port, Γ_{TS} is the reflection coefficient of the transfer standard, and Γ_X is the reflection coefficient of the unknown wattmeter. The factor, Γ_G, is defined by Engen [4] as the equivalent generator reflection coefficient of the high-power source, and is given in terms of the coupler's scattering parameters

$$\Gamma_G = S_{22} - \frac{S_{21}\,S_{32}}{S_{31}}, \qquad (2)$$

where the input of the source's coupler is designated port 1, the output of the source's coupler is designated port 2, and the sidearm of the source's coupler is port 3.

The process of calculating P_X may be divided into two stages : (1) calibration of the high-power source using the calibrated transfer standard; and (2) calibration of an unknown wattmeter using the calibrated high-power source. Figure 1 illustrates the measurement system.

3.1. Calibration of High-Power Source with Transfer Standard

Manipulation of eq (1) yields

$$\frac{P_{TS}\,|1 - \Gamma_G \Gamma_{TS}|^2}{P_{CT}} = \frac{P_X\,|1 - \Gamma_G \Gamma_X|^2}{P_{CX}}. \qquad (3)$$

Let

$$K_e = \frac{P_{TS}\,|1 - \Gamma_G \Gamma_{TS}|^2}{P_{CT}}. \qquad (4)$$

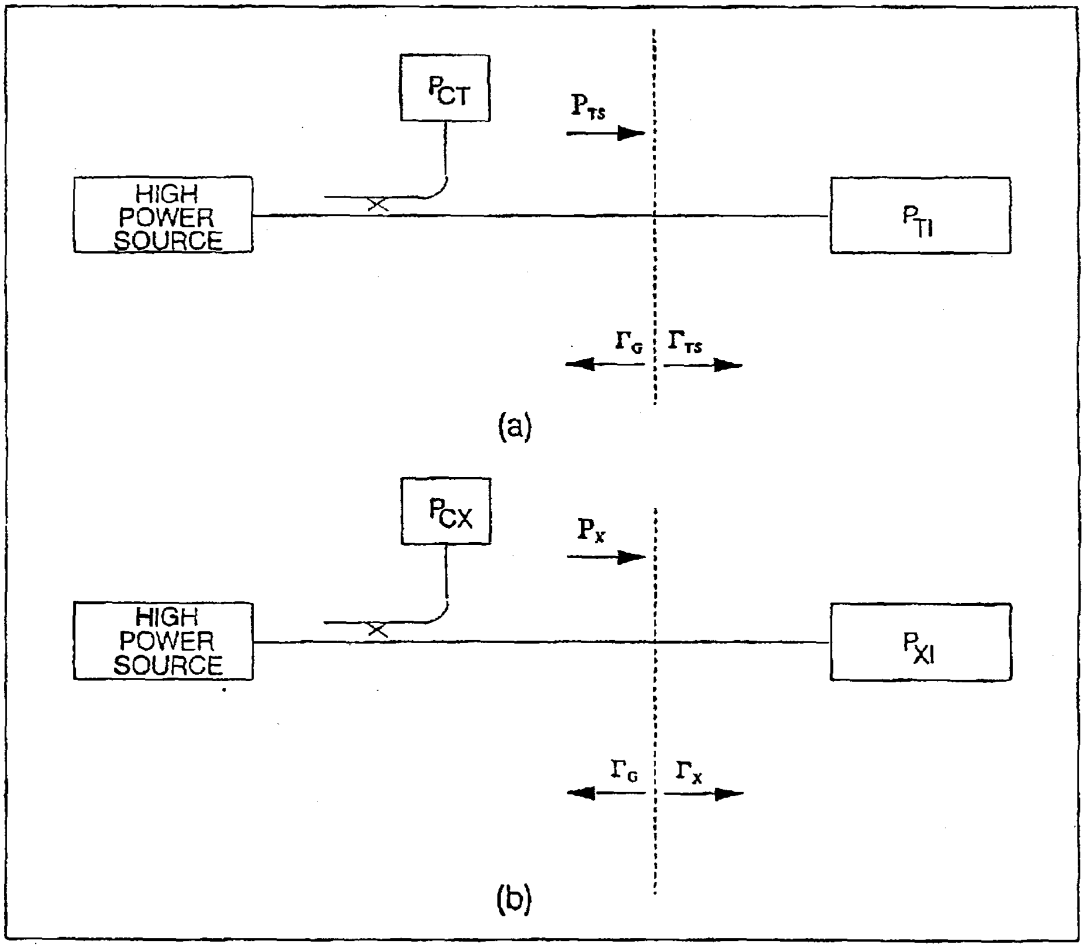


Figure 1. Basic circuit. (a) With the NIST transfer standard connected to the high power source. (b) With the wattmeter under calibration connected to the high power source.

where the calibration factor of the high-power source, K_e, is defined as the ratio of the rf power incident upon a nonreflecting transfer standard to the power read by the high-power source.

The incident power on the transfer standard, P_{TS}, is given by

$$P_{TS} = \frac{P_{TI}}{K_f}, \tag{5}$$

where P_{TI} is the indication of the transfer standard and K_f is the calibration factor of the transfer standard obtained from a cascaded coupler calibration.

Substituting eq (5) into eq (4) yields

$$K_e = \frac{P_{TI}\,|1 - \Gamma_G \Gamma_{TS}|^2}{K_f\, P_{CT}}. \tag{6}$$

At a given frequency and power level, one can calculate K_e by reading the indication of the transfer standard and high-power source if values for Γ_G, Γ_{TS}, and K_f are known.

3.2. Calibration of Unknown Wattmeter with Calibrated High-Power Source

Once the high-power source has been calibrated with a transfer standard, the source can be used to calibrate any number of unknown terminating wattmeters. A calibrated source saves the user form having to perform a laborious cascaded coupler calibration each time a wattmeter is to be measured..

Inserting eq (3) into eq (4) gives

$$K_e = \frac{P_X\,|1 - \Gamma_G \Gamma_X|^2}{P_{CX}}. \tag{7}$$

Equation (7) can be written as

$$P_X = \frac{K_e\, P_{CX}}{|1 - \Gamma_G \Gamma_X|^2}. \tag{8}$$

Substituting K_e, defined in eq (4), into eq (8), one ends up with the initial definition of P_X, in eq(1).

The calibration factor of the unknown wattmeter, K_x, is defined as

$$K_x = \frac{P_{XI}}{P_X}, \tag{9}$$

where P_{XI} is the indication of the unknown wattmeter. At a given frequency and power level, K_x can be calculated by reading the indication of the unknown wattmeter and the high-power source if values for Γ_G, Γ_X, and K_e are known. The factor, K_x, may be expanded by inserting eq (6) into eq(8), and inserting eq(8) into eq(9), which gives

$$K_x = \frac{P_{XI}}{P_{TI}}\,\frac{P_{CT}}{P_{CX}}\,K_f\,\frac{1}{MM}, \tag{10}$$

where the mismatch term, MM, is

$$MM = \frac{|1 - \Gamma_G \Gamma_{TS}|^2}{|1 - \Gamma_G \Gamma_X|^2}. \tag{11}$$

4. Measurement Results

4.1. Calibration of High-Power Source with Transfer Standard

The high-power source was calibrated at 1, 10, 100, 500, and 1000 W at selected frequencies from 2 to 30 MHz and at 1, 10, 100, 300, and 500 W at frequencies from 30 to 400 MHz.

The calibration factors for the high-power source are near unity at all powers since its indication is in watts. The source has its own built-in calibration constants programmed in from the factory. These constants were not altered; rather, the source was treated as an uncalibrated unit. The calibration factors, determined from attaching the transfer standard, are stored in the computer's memory. Likewise, the transfer standard's and unknown wattmeter's calibration factors are stored in the computer's memory.

4.2. Calibration of Unknown Wattmeter with Calibrated High-Power Source

Both wattmeters were calibrated at 1, 10, 100, 500, and 1000 W at frequencies from 2 to 30 MHz, and at 1, 10, 100, 300, and 500 W at frequencies from 30 to 400 MHz.

The calibration factors are near unity at all power levels since the wattmeter measures power directly with a diode detector. The calibration factors differ among the wattmeters, and at each frequency the factors increase with power, partly due to the nonlinearity in the diode detector.

Both wattmeters were calibrated using the cascaded coupler technique and by a direct connection to the high-power source. Figures 2 and 3 show the comparisons of the calibration factors at 1 and 500 W for Wattmeter 1 and Wattmeter 2, respectively.

5. Uncertainty Analysis

5.1. Systematic Uncertainty

The systematic uncertainty of the calibration process, Δ, can be defined, using eq (10), as

$$\Delta = \sqrt{(\Delta_{PXI})^2+(\Delta_{PTI})^2+(\Delta_{PCT})^2+(\Delta_{PCX})^2+(\Delta_{KF})^2+(\Delta_{MM})^2}, \tag{12}$$

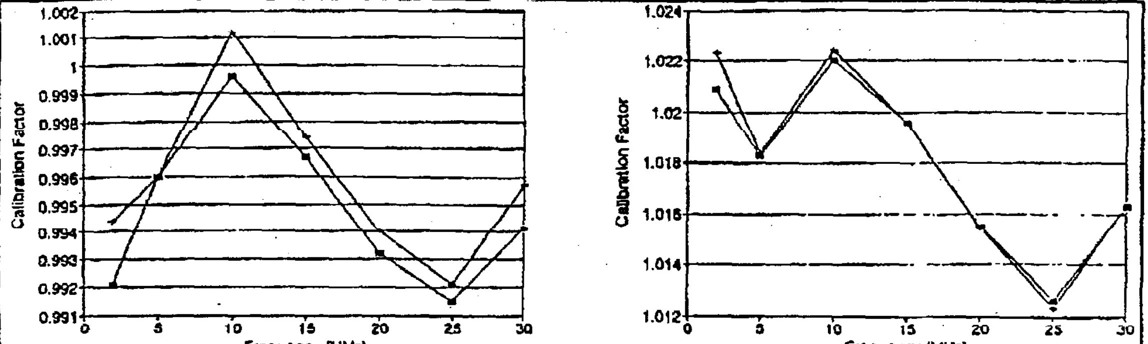
where: Δ_{PXI} is the uncertainty of the unknown wattmeter indication, Δ_{PTI} is the uncertainty of the transfer standard indication, Δ_{PCT} is the uncertainty of the high-power source indication with the transfer standard connected, Δ_{PCX} is the uncertainty of the high-power source indication with the unknown wattmeter connected, Δ_{KF} is the uncertainty of the transfer standard's calibration factor, and Δ_{MM} is the uncertainty of the mismatch term.

5.1.1. Uncertainty of Transfer Standard's Indication The uncertainty of the transfer standard's indication is due to the resolution of its digital readout. The lowest resolution at a calibrated power is when three digits are displayed at 300 W, resulting in a ±0.17% uncertainty.

5.1.2. Uncertainty of Unknown Wattmeter's Indication Assuming the unknown wattmeter is the same model as the transfer standard, its worst case resolution is also ±0.17%.

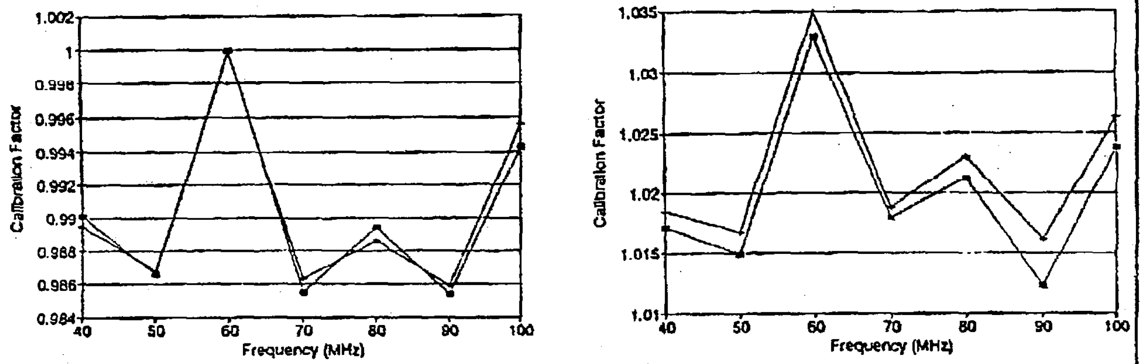
5.1.3. Uncertainty of High-Power Source There are several uncertainties due to the radio frequency source, most of which are negligible. Harmonics are at least 46 dB below the fundamental signal at the output port, thus having negligible effects. Spurious signals are also negligible since they are approximately -60 dBc.The frequency uncertainty is approximately ±0.001% due to the internal free-air crystal oscillator of the rf source. The rf source amplitude stability is specified by the manufacturer to be ±0.12%.

5.1.4. Uncertainty of Transfer Standard's Calibration Factor It has been determined that the systematic uncertainty of the transfer standard's calibration factor is ±0.67% [1]. Individual components that are taken into account include: uncertainty in the dc voltmeter measurements, uncertainty in the Type IV power meters, dual-element substitution errors in the thermistor mounts, uncertainty in the 10 mW standard mount calibration factor, mismatch uncertainty,



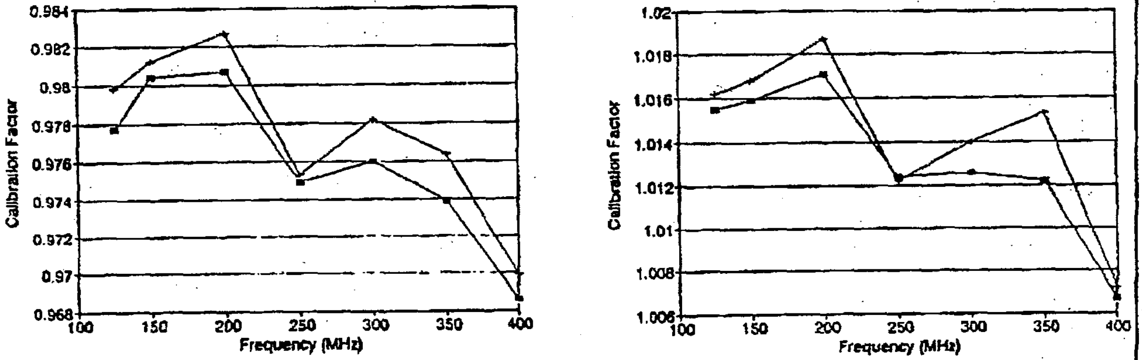
(a) Comparisons from 2-30 MHz at 1 W.

(b) Comparisons from 2-30 MHz at 500 W.



(c) Comparisons from 40-100 MHz at 1 W.

(d) Comparisons from 40-100 MHz at 500 W.

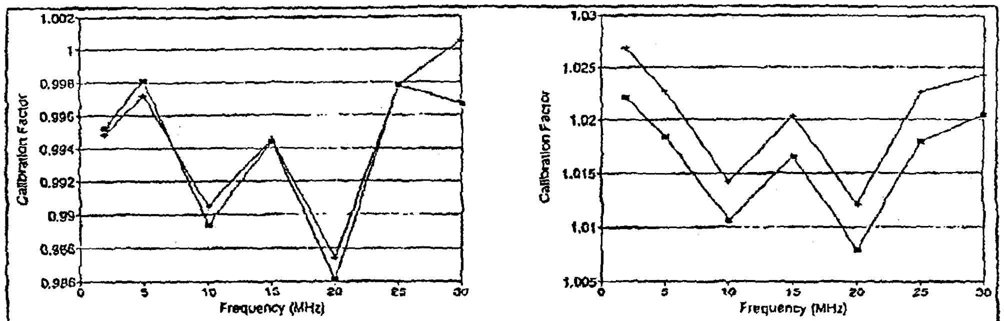


(e) Comparisons from 125-400 MHz at 1 W.

(f) Comparisons from 125-400 MHz at 500 W.

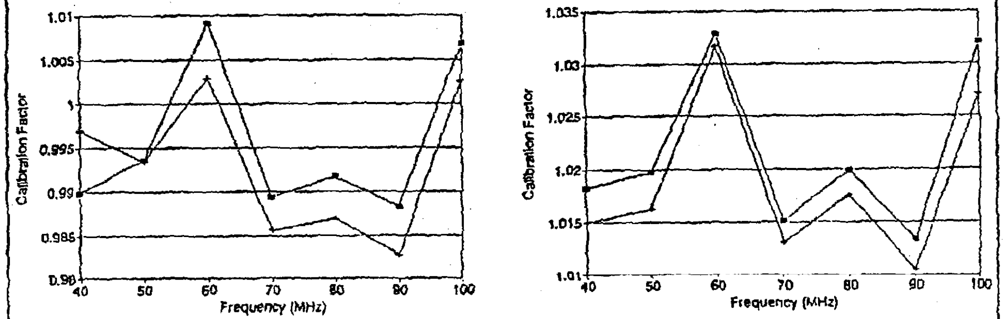
—■— Cascaded Coupler —+— Source Transfer

Figure 2. Calibration with high power source versus calibration with cascaded coupler technique for Wattmeter 1.



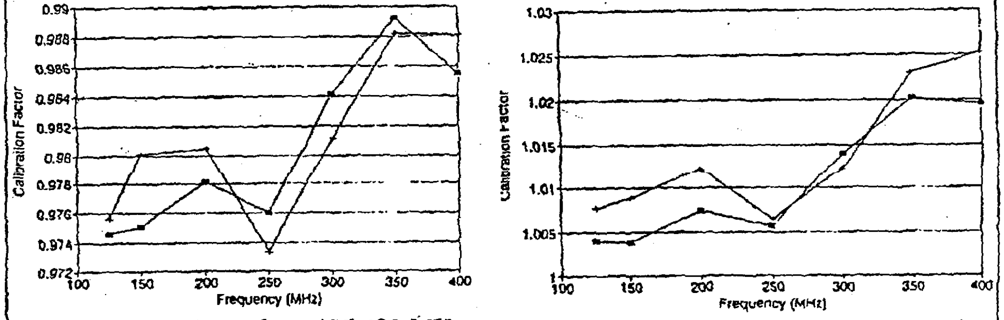
(a) Comparisons from 2-30 MHz at 1 W.

(b) Comparisons from 2-30 MHz at 500 W.



(c) Comparisons from 40-100 MHz at 1 W.

(d) Comparisons from 40-100 MHz at 500 W.



(e) Comparisons from 125-400 MHz at 1 W.

(f) Comparisons from 125-400 MHz at 500 W.

—■— Cascaded Coupler —+— Source Transfer

Figure 3. Calibration with high power source versus calibration with cascaded coupler technique for Wattmeter 2.

nonlinearities in the cascaded couplers, and uncertainty in the high-power source.

5.1.5. Uncertainty of Mismatch Term Since the impedances of the transfer standard and the unknown wattmeter are not equal, mismatch is introduced when the transfer standard is replaced by the wattmeter. The mismatch term, discussed earlier, is given by

$$MM = \frac{|1 - \Gamma_G \Gamma_{TS}|^2}{|1 - \Gamma_G \Gamma_X|^2} . \qquad (13)$$

It can be shown that the uncertainty of the mismatch term, Δ_{MM}, can be approximated by

$$\Delta_{MM} = \frac{1 \pm 2\,(|\Gamma_G| \pm \Delta|\Gamma_G|)(|\Gamma_{TS}| \pm \Delta|\Gamma_{TS}|)}{1 \pm 2\,(|\Gamma_G| \pm \Delta|\Gamma_G|)(|\Gamma_X| \pm \Delta|\Gamma_X|)} . \qquad (14)$$

where $\Delta|\Gamma_G|$ is the uncertainty of the equivalent generator reflection coefficient, $\Delta|\Gamma_{TS}|$ is the uncertainty of the transfer standard reflection coefficient, and $\Delta|\Gamma_X|$ is the uncertainty of the unknown wattmeter reflection coefficient [1]. The uncertainty of Γ_G is almost entirely due to the uncertainty of S_{22}. The resultant mismatch uncertainty is calculated to be ±0.20%

5.1.6. Overall Systematic Uncertainty A summary of all systematic uncertainty components and the total as calculated by the root-sum-of-squares method are shown in table 1. The overall systematic uncertainty is ±0.76%.

5.2. Random Uncertainty

Each stage of the calibration was repeated several times to calculate random uncertainties. The calibration of Wattmeter 1, using the cascaded coupler technique, was repeated ten times at all powers and frequencies. Likewise, the calibration of the high-power source, using the calibrated Wattmeter 1, was repeated ten times. Wattmeters 1 and 2 were calibrated five times each using the calibrated high-power source.

5.3. Total Uncertainty

The total uncertainty, U_T, may be calculated using the equation

$$U_T = 2\sqrt{\frac{\Delta^2}{3} + \frac{S_F^2}{N_F} + \frac{S_C^2}{N_C} + \frac{S_X^2}{N_X}} , \qquad (15)$$

Uncertainty source	Contribution (%)
Transfer Standard Indication	± 0.17
Unknown Wattmeter Indication	± 0.17
High Power Source with Transfer Std. Connected	± 0.12
High Power Source with Unk. Wattmeter Connected	± 0.12
Calibration Factor of Transfer Standard	± 0.67
Mismatch Due to Reflection Coefficients	± 0.20
Total (RSS)	± 0.76

Table 1. Systematic uncertainty components.

where Δ is the systematic uncertainty of the entire calibration process, S_F is the standard deviation of the transfer standard calibration repeated N_F times, S_C is the standard deviation of the source calibration repeated N_C times, and S_X is the standard deviation of the unknown wattmeter calibration repeated N_X times. Table 2 lists the systematic uncertainty and the ranges of values for the random uncertainties and total uncertainties for both wattmeters.

6. Conclusion

The calibration of high-power cw wattmeters may be accomplished in one of two ways: (1) the extension of power measurement, using cascaded couplers, traceable to a 10 mW standard thermistor mount, or (2) direct comparison against a calibrated high-power source. Each method has its advantages. Using the direct comparison technique, the overall uncertainties are higher. This method, however, takes less time and requires fewer connections. In the end, the user must decide what is most important.

Acknowledgements

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7. References

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About The Authors

Jeffrey A. Jargon was born in Denver, Colorado on December 15, 1967. He received a Bachelor of Science degree in Electrical Engineering in 1990 from the University of Colorado at Boulder, and is currently enrolled in the Master of Science

	Systematic Uncertainty (%)	S_F (%)	S_c (%)	S_x (%)	Total Uncertainty (%)
Wattmeter 1	0.76	0.07-0.66	0.06-0.43	0.06-0.68	0.88-1.18
Wattmeter 2	0.76	0.07-0.66	0.06-0.43	0.04-0.41	0.88-1.07

Table 2. Systematic uncertainty and ranges of the random and total uncertainties of the wattmeters.

program. He joined the National Institute of Standards and Technology in the Microwave Metrology Group, where his main responsibilities are in cw, coaxial high power and high frequency voltage metrology.

Gregorio Rebuldela was born in Hilo, Hawaii. He received his B.S. degree in Electrical Engineering from the University of Colorado in 1962. He joined the National Institute of Standards and Technology where he first engaged in developing and evaluating high frequency, coaxial voltage standards and measurement systems. He has worked on the development of the low frequency dual six-port automatic network analyzer which measures the circuit parameters of one and two port devices. His current technical responsibilities as project leader include developing and evaluating cw, coaxial high power measurement systems and transfer standards; and improving and maintaining the high frequency rf voltage and low power calibration services.