A REVISED UNCERTAINTY ANALYSIS FOR THE NIST 30-MHZ ATTENUATION CALIBRATION SYSTEM *

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Abstract

Although the 30-MHz Attenuation Calibration System has been in operation for many years at the National Institute of Standards and Technology, several modifications have been made to the system since the last published uncertainty analysis. The linear displacement of the standard attenuator's receiving coil is now measured with a laser interferometer instead of a steel ruled scale and optical projector, and a new comparison receiver has been installed in the system. The expanded uncertainty is on the order of $\pm$ 0.003 dB per 10 dB step. Type A uncertainties depend upon the repeatability and resettability of the system and the device under test. Type B uncertainties are due to the standard waveguide below-cutoff (WBCO) attenuator, the resolution of the comparison receiver, the change in level of the precision phase shift standard, the level set attenuator, rf leakage, and mismatch uncertainty. The individual uncertainty components are stated and combined to fully comply with the new NIST policy on statements of uncertainty.

1. Introduction

The accurate measurement of the attenuation of energy in coaxial and waveguide transmission lines is a fundamental requirement in the design, development, and operation of most electronic systems. Attenuators which decrease rf energy in a precisely known way must be calibrated by comparison with reference standards maintained by or traceable to NIST. For both technical and historical reasons, many rf, microwave, and millimeter wave measurements over the entire frequency spectrum are ultimately referenced to 30-MHz calibrations.

Over the past forty years, many papers have been published about the measurement techniques and uncertainties regarding attenuation calibrations. The purpose of this paper is two-fold: (1) to reflect the recent modifications made to the system since the last published uncertainty analysis [1]; and (2) to explain the combination and terminology of uncertainties for complying with the new NIST policy on statements of measurement results [2].

2. System Description

A basic block diagram of the unmodulated dual-channel system employed by NIST at 30-MHz is shown in Fig. 1. A dual-channel nulled system has fewer problems of level instability in the source and has high sensitivity. The drawback is that both phase and magnitude adjustments must be made; these adjustments increase the complexity of the system. A range of attenuation measurement in excess of 100 dB may be obtained with this system by placing the device under test (DUT) in the insertion point. Measurements of incremental attenuation are made by adjusting the standard WBCO attenuator and phase shift standard until a null response is obtained. The resolution is very high for large signal amplitudes. Better resolution can be maintained at small signal amplitudes by using quadrature detection rather than a simple nulling approach. To obtain a successful system, a precision phase shifter of constant amplitude or one with precisely known losses is required to achieve the null, or quadrature phasing of the two channels.

3. Type A Evaluation of Standard Uncertainty

A Type A evaluation of standard uncertainty may be based on any valid statistical method for treating data. Examples are calculating the standard deviation of the mean of a series of independent observations, using the method of least squares to fit a curve to data in order to estimate the parameters of the curve and their standard deviations, and carrying out an analysis of variance in order to identify and quantify random effects in certain kinds of measurements [2].

The Type A uncertainty quoted to a customer depends upon the repeatability and the resettability of the system and the device under test. Normally, three trials are performed to arrive at a Type A uncertainty. The sample standard deviation is calculated at each attenuation level. A typical Type A standard uncertainty is $\pm$ 0.001 dB per 10 dB step.

4. Type B Evaluation of Standard Uncertainty

A Type B evaluation of standard uncertainty is based upon scientific judgment using all of the available relevant information. This includes previous measurement data, manufacturer's specifications, data provided in calibration reports, knowledge of the behavior of relevant instruments and materials, and uncertainties assigned to reference data taken from handbooks [2].

The Type B evaluation of standard uncertainty accounts for the following factors:

a. Uncertainty of the standard WBCO attenuator.
b. Resolution of the comparison receiver.
c. The change in level over the range of the precision phase shifter.
d. Uncertainty of the level set attenuator.
e. RF leakage.
f. Mismatch uncertainty.

4.1. Standard WBCO Attenuator

The standard is a circular waveguide-below-cutoff (WBCO) attenuator , commonly called a piston attenuator [1]. The brass waveguide has an outer diameter of 9.906 cm (3.9 inches) and a length of 56.642 cm (22.3 inches). The internal diameter of the guide is approximately 8.128 cm (3.2 inches) and was chosen to give an attenuation rate of 10 dB / 2.54 cm (1 inch). The inside wall of the guide is coated with 0.127 to 0.254 μm (5 to 10 microinches) of rhodium. This provides a hard surface for the silver sliding contacts of the piston and prevents corrosion of the brass surface. The effective conductivity of the guide surface is insignificantly altered from that of brass itself.

Dimensional tolerances of the guide and the resolution and accuracy with which the displacement between the exciting and receiving coils can be measured are very important. The guide diameter must remain constant and be perfectly circular. Any ellipticity in the guide will cause the propagation constant to differ from the circular case, thereby possibly exciting degenerate modes of propagation. Angular variations along the major axis will produce undesirable variations in the exponential decay of the field within the waveguide.

The uncertainties of the standard WBCO attenuator presented are taken from the measurements and calculations by Allred and Cook [3], with the exception of the linear displacement of the receiving coil.

4.1.1. Internal Waveguide Diameter The internal diameter of the guide was measured at 5.08 cm (2 inch) intervals along the guide using an air gauge. The average diameter was 8.12102 cm (3.19725 inches) with a maximum variation of 0.00008 cm (0.00003 inches). The uncertainty of the measurements are within ± 127 millionths of a cm (± 50 millionths of an inch). These measurements were made at 20°C (68°F) while the system may be operated at up to 2.2°C (4°F) above this temperature. The uncertainty of the diameter results in a contributed uncertainty of ± 0.0003 dB per 10 dB step.

4.1.2. Linear Displacement of Receiving Coil The displacement of the receiving coil relative to the launching coil is measured with a laser interferometer. The components of uncertainty due to the laser interferometer include optical resolution, nonlinearity of the interferometer, environmental effects, and the optics installation effects. A conservative value for the overall uncertainty is approximately ± 0.0001 dB per 10 dB step. This uncertainty is minimized by using a device to compensate for changes in the initial environmental conditions, housing the interferometer in a shield to protect it from large temperature gradients, and careful installation of the optical components.

4.1.3. Velocity of Electromagnetic Waves in Guide With the operating frequency so far below the cutoff frequency, the effect of air, as opposed to a vacuum, within the guide gives rise to an uncertainty less than 1 part in 10^7, which is negligible compared to the other components.

4.1.4. RF Conductivity of Guide The dc conductivity of the guide was found to be 1.35×10^7 siemens per meter. If the rf conductivity does not change more than 5% from the dc value, the uncertainty is ± 0.0003 dB per 10 dB step.

4.1.5. RF Permeability of Guide The rf permeability is negligible for a brass waveguide and does not affect uncertainty.

4.2. Resolution of the Comparison Receiver

The 30-MHz comparison receiver is an rf null detector designed for extremely high sensitivity consistent with simplicity of operation. The detector is frequency-locked to the signal to be examined and thus requires a synchronous reference voltage to achieve its high sensitivity. A single gain control adjusts the sensitivity. The null signal is indicated by two front panel center-indicating meters. A variable phase control enables in-phase and quadrature components of the null signal to be displayed individually on separate meters.

The resolution of the receiver is 0.001 dB when measuring a 100 dB change in attenuation on a piston attenuator (with an initial insertion loss of 30 dB). Thus, the detection system has an attenuator resolution of 0.001 dB at 130 dB below the maximum output from the standard attenuator.

4.3. Precision Phase Shift Standard

The precision phase shift standard used at NIST consists of a sliding airline trombone configuration. The range of the standard phase shifter is 38° or 101.6 cm (40 inches) of travel. The change in level over the entire range is less than $\pm$ 0.0005 dB. This range is adequate when calibrating attenuators since piston attenuators normally have negligible phase shift. The phase shift in dissipative attenuators approximates their physical length, which is a small fraction of the standard phase shifter travel.

4.4. Level Set Attenuator

The level set attenuator is a TM mode WBCO attenuator consisting of a variable capacitor formed by mating hemispherical electrodes inside a cylindrical brass waveguide. One of the electrodes is motor-driven so that the spacing between the two can be varied, thus changing the value of attenuation in the waveguide. This attenuator produces very little phase shift since the mode has no significant skin depth penetration.

This attenuator does not contribute to the uncertainty since it is not changed during a specific incremental measurement.

4.5. Maximum RF Leakage

The uncertainties due to rf leakage are difficult to measure precisely. The entire calibration system is extremely well shielded to prevent problems caused by rf leakage. The rf power source is housed in a solid-copper, shielded room; all interconnecting cables are made of semirigid coaxial lines; all coaxial connectors are painted with conducting paint to prevent rf radiation; and the outer conductors of the semirigid lines are all tied to ground. These precautions reduce the possibility of significant rf leakage. The portion of the total systematic uncertainty due to rf leakage is assumed to be 80 dB below the signal or $\pm$ 0.0009 dB per 10 dB step, which is a conservative estimate.

4.6. Mismatch Uncertainty

The uncertainty due to impedance mismatches when calibrating attenuators on this system has been calculated using the VSWR's of the system and a typical attenuator being calibrated. The VSWR of this system is approximately 1.01. Variable attenuators which are calibrated on this system have a similar VSWR. Therefore, calculations are based on the assumption of a maximum VSWR of 1.02, which translates to a reflection coefficient, Γ, of 0.0099. Mismatch loss [4] in decibels is calculated using

$$L_{MM} = -10\log_{10}(1-\Gamma^2) \quad . \quad (1)$$

Thus, a mismatch uncertainty of $\pm$ 0.0004 dB is typical.

When the device under calibration is a WBCO attenuator, the mismatch uncertainty is virtually negligible due to the high initial insertion loss of the device.

4.7 Overall Type B Uncertainty

In each of the Type B components, an estimated range, $\pm$ a_j, is given, assuming that the quantity in question has a 100 % probability of lying within that interval. The quantity is treated as if it is equally probable for its value to lie anywhere within the interval. Therefore, it is modeled by a rectangular probability distribution. The best estimate of the standard deviation, u_j, is

$$u_j = \frac{a_j}{\sqrt{3}} \ . \qquad (2)$$

Table 1 shows all of the known Type B components along with their corresponding uncertainties and standard deviations. The overall standard deviation of the Type B components, calculated using the root-sum-of-squares method (RSS), is $\pm$ 0.001 dB per 10 dB step.

5. Combined Standard Uncertainty

The combined standard uncertainty, u_c, is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard deviations, u_i, whether arising from Type A evaluation or Type B evaluation [2]. The technique used to combine the standard deviations is the RSS method.

The total uncertainty reported is the expanded uncertainty, U, which is obtained by multiplying u_c by a coverage factor, k. To be consistent with current international practice, the value of k used at NIST for calculating U is k=2. Using a typical value for the Type A standard deviation of $\pm$ 0.001 dB as stated in section 3, a typical value for U is $\pm$ 0.003 dB per 10 dB step.

6. Conclusion

By revising the uncertainty analysis for the NIST 30-MHz Attenuation Calibration System, customers will now receive a calibration report showing Type A and Type B standard deviations rather than the familiar systematic and random uncertainties. The total reported uncertainty will reflect recent modifications to the system and compliance with the new NIST policy on statements of uncertainty.

Acknowledgements

I would like to express my sincere thanks to the following people: Robert M. Judish for his help with the statements of uncertainty; David H. Russell and Douglas D. Sutton for their consultations regarding the system; Tuan Lam for reviewing this paper; Greg Rebuldela for his kind support; and Young-Sook Jargon and my family for their love.

7. References

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About the Author

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 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 30-MHz attenuation measurements.

Table 1. Type B components of the 30-MHz Attenuation System with corresponding uncertainties and standard deviations.

Component	Range (dB per 10 dB step)	Standard Deviation (dB per 10 dB step)
Standard WBCO Attenuator		
Internal Waveguide Diameter	± 0.0003	± 0.0002
Linear Displacement of Receiving Coil	± 0.0001	± 0.0001
Velocity of Electromagnetic Waves in Guide	Negligible for Air	---
RF Conductivity of Guide	± 0.0003	± 0.0002
RF Permeability of Guide	Negligible for Brass	---
Resolution of Comparison Receiver	± 0.001	± 0.0006
Precision Phase Shift Standard	± 0.0005	± 0.0003
Level Set Attenuator	Negligible	---
Maximum RF Leakage	± 0.0009	± 0.0005
Mismatch Uncertainty	± 0.0004	± 0.0002
Combined Standard Uncertainty (RSS)		**± 0.001**

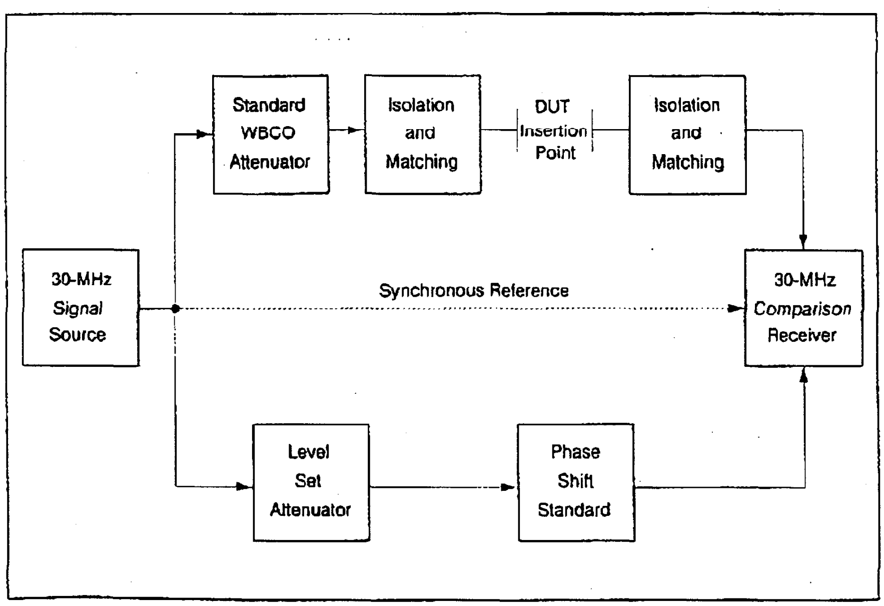

Fig. 1. Basic block diagram of the 30-MHz dual-channel attenuation calibration system.