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Uncertainty Assessment for Standard Antenna Measurements on the Open Area Test Site

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Uncertainty Assessment for Standard Antenna Measurements on the Open Area Test Site

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The National Institute of Standards and Technology calibrates electromagnetic compatibility antennas using the standard antenna method. This method uses a standard antenna to precisely measure the electric field at a location. An antenna under test is placed where the standard antenna was located to determine its antenna factor. Complete uncertainties are determined for calibrations performed on the open-area-test-site leading to a statement of uncertainty of the method. The results of this procedure yield a standard uncertainty of 0.4 dB. Assessment of this uncertainty statement and its details are presented in this paper.

Keywords: uncertainty analysis, open area test site, electromagnetic compatibility, measurement, standard antenna, antenna factor.

1. Background of OATS Measurements at NIST

The National Institute of Standards and Technology (NIST) calibrates antennas for testing of electromagnetic compatibility (EMC). NIST uses the standard antenna method (SAM) to determine antenna factor in reference [1]. This method relies on a fundamental antenna (a half-wave dipole) and a simplified converter (a diode) whose determination of a linearly polarized continuous-wave, electric field (CW E-field) is easily calculable. This method also is independent of the condition of the ground plane since it measures the E-field at the test location. This allows for repeatable measurements of the E-field on the open area test site. Only steady-state, continuous-wave rf fields with sinusoidal time variation are measured.

2. Description of the Standard Antenna Method

The standard antenna method uses a set of half-wave ($\lambda/2$) dipoles designed and built at NIST. The standard antennas are self-resonant, half-wave dipoles with a high-impedance Shottky diode across the center gap and cover the frequency range of 30 MHz to 1000 MHz in incremental steps. Currently, the available measurement frequencies are 30 MHz to 100 MHz every 10 MHz, 100 MHz to 300 MHz every 25 MHz, 300 MHz to 600 MHz every 50 MHz, and 600 MHz to 1000 MHz every 100 MHz.

Briefly, the SAM uses a standard antenna to measure the E-field at a location. Then the antenna under test (AUT) replaces the standard antenna and its response to that E-field is measured. An rf-to-dc voltage transfer function is determined before each test to characterize the response of the standard antenna to rf signals. The E-field is calculated from the standard antenna's dc response, the voltage transfer function, and its physical and electrical characteristics. The antenna factor of the AUT is a ratio of the measured E-field to the AUT's response. Details of the NIST standard antenna and this method for measuring the magnitude of an E-field are in reference [1].

The primary equations for determining the antenna factor for an AUT using the standard antenna method are:

$$E = V_{oc} / L_{eff} \tag{1a}$$

$$V_{oc} = M \cdot V_{dc} + B \tag{1b}$$

$$K_{dB} = E_{dB} - (V_{dB} + CL_{dB} + SA_{dB}) \tag{1c}$$

where

E = electric field strength, V/m,
V_{oc} = open circuit rf voltage of NIST standard antenna, V,
M = linear fit coefficient (slope),
B = linear fit coefficient (Y intercept point), V,
V_{dc} = dc voltage response of NIST standard antenna, V,
L_{eff} = effective length of the NIST standard antenna, m,
K_{dB} = antenna factor of antenna under test, dB/m,
E_{dB} =(20*log(E)), electric field strength, dB (re 1V) /m,
V_{dB} = response of antenna-under-test from the electric field, dB (re 1V),
CL_{dB} = insertion loss of the cable, dB, and
SA_{dB} = correction factor for the receiver, dB.

3. Explanation of Test Setups and Measurement Equipment

The SAM consists of two parts, (1) the determination of the rf-to-dc voltage transfer function of the standard antenna performed inside the laboratory, and (2) the measurement of the E-field and the AUT's response on the OATS.

Figure 1 shows the first measurement setup as a block diagram. The *rf source* consists of a rf signal generator, a low power (5 W) amplifier, and a low-pass filter. The *rf power monitor* is a calibrated dual-directional coupler, calibrated coaxial cables, and calibrated power sensors and meter. The *180° hybrid* and pair of customized coaxial t-connectors with 50 Ω loads provide a controlled rf signal to the standard antenna's feed point. The dc voltage output from the standard antenna mount is measured by the *dc voltmeter* with a 100 MΩ load across its input.

Figure 1. Block diagram of the setup to measure the rf-to-dc voltage transfer function for the NIST standard antenna mounts.

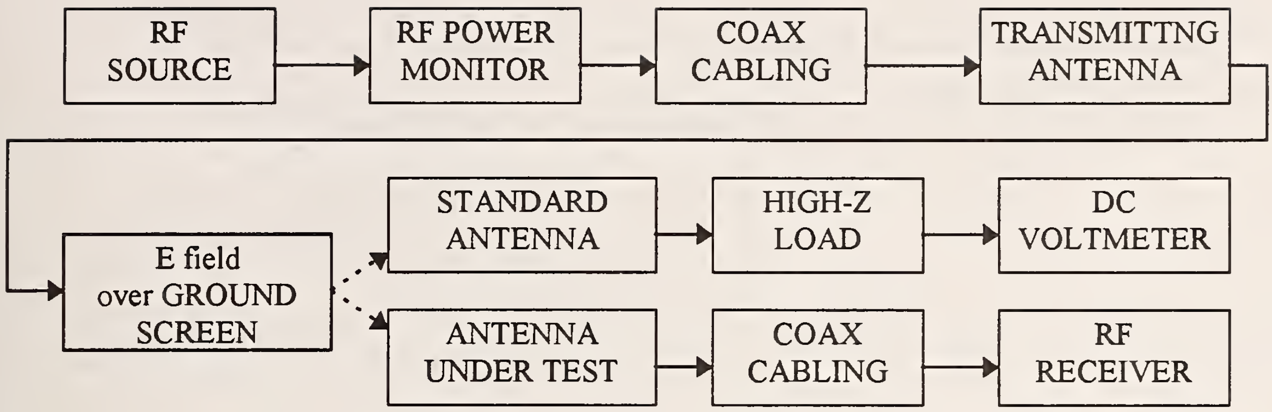

Figure 2. Block diagram of the Standard Antenna Measurement on the OATS.

The second part of the SAM is a measurement of the E-field and the AUT's response. This is a two-step sequential process. As figure 2 shows, this sequence involves a change on the receiving side of the setup. The *rf source* and *rf power monitor* blocks are as described earlier, but with a larger rf amplifier (80 W) with the source. The *transmitting antenna* is either a tuned dipole (30 MHz -125 MHz) or a log-periodic antenna (125 MHz -1000 MHz) mounted on a height adjustable tripod. The *E-field over ground screen* symbolizes the interaction of the transmitted field with the environment of the OATS. This interaction includes intrusive ambient signals, reflections off nearby objects (including the test equipment), and reflections off the ground plane. The blocks for *standard antenna* and *antenna under test* represent the antennas used in the test. The *high-Z load* is a 100 MΩ load that is placed across the *dc voltmeter's* input to regulate the signal from the standard antenna. The *rf receiver* is a calibrated spectrum analyzer configured to predetermined settings. All of the equipment, except for the antennas and cables, reside below the 30 m by 60 m ground plane in an underground room.

4. Assessment of Uncertainties

Even though reference [1] details the standard antenna method at NIST, the description of the uncertainties of the measurement is cursory when compared to present requirements. With the current emphasis on statement of uncertainties in EMC antenna measurements around the globe, a further look at uncertainties of the SAM is merited. Reference [2] is a NIST document that provides guidelines for uncertainty analysis. Several other publications listed as references [3 to 5] offer procedures for EMC antenna measurements that range from general guidelines to specific steps. This study agrees with and will follow those procedures. Also, in agreement with these publications, uncertainties will be expressed in decibels.

The individual uncertainties $u(x_i)$ in the Standard Antenna Method will be examined using the previous equations (1a to 1c) and the block diagrams (figures 1 and 2). The following are identified as sources of uncertainty:

(1) rf-to-dc transfer function of the standard antenna, $u_{rf\text{-}dc}$
(2) effective length of the standard antenna, u_{Leff}
(3) dc voltage measurement of the standard antenna, u_{dc}
(4) rf voltage measurement of the AUT, u_{rf}
(5) measurement of loss in the receiving cable, u_{cbl}
(6) rf source stability, u_{source}

(7) alignment of antennas on OATS, u_{align}
(8) E-field uniformity, u_{ufm}
(9) measurement repeatability and E-field environmental interaction, u_{rept}

Each of these terms will be looked at to determine its influence on the combined standard uncertainty. Terms that are based on measured data will be plotted as data in a graph. The measured terms will also be presented in a graph as a histogram of the data. A histogram is a graphical representation of the number of measurement values that fall in a sequence of "bins" which partition the continuous range of measurement values. This tool provides information based on the number of occurrences of a value in a data set when repeated measurements are made. That is, it presents a distribution of the data showing the spread and shape of the measured data. For example, for data from 0 dB to 0.25 dB (the range of data), the histogram would show the number of data for each 0.05 dB range (the bins) and the cumulative percentage of data as the bins increased from 0 dB to 0.25 dB in steps of 0.05 dB.

We can apply a general formula for propagation of independent uncertainties from reference [2] to obtain the combined standard uncertainty. This equation can also be used if any individual uncertainty has more than one term of influence. For a general linear function, the combined standard uncertainty is

$$u_c = \sqrt{\sum_{i=1}^{N} \left(u(x_i)\right)^2} \,. \qquad (2)$$

Incorporating the terms from the above uncertainty list and using eq (2),

$$u_c = \sqrt{(u_{rf-dc})^2 + (u_{Leff})^2 + (u_{dc})^2 + (u_{rf})^2 + (u_{cbl})^2 + (u_{source})^2 + (u_{align})^2 + (u_{ufm})^2 + (u_{rept})^2} \,. \qquad (3)$$

We inspect each individual term in sections 4.1 to 4.9 to determine its effect on the combined standard uncertainty.

Instrument calibrations influence several uncertainty terms in this test. These components are included where appropriate. All of the instrumentation used in the SAM measurements are traceable to NIST standards, either calibrated by the manufacturer or through internal measurements. Instruments used in SAM are a power meter and sensor, an rf spectrum analyzer, a dc voltmeter, and a signal generator.

The Radio-Frequency Fields Group at NIST has a calibrated NIST type-IV power meter as described in reference [6] with a thermocouple sensor that is calibrated at NIST. The worst-case uncertainty specification on the power sensor calibration is 0.5 percent from reference [7]. This power sensor and type-IV power meter combination is used to calibrate the power meter and sensors and the spectrum analyzer used in the measurement.

The amplified signal source depends upon the combined signal generator and the amplifier output. The power output of the signal generator is a relative value for the SAM and therefore only the resolution of the device is pertinent. The manufacturer-rated resolution for the output power is 0.1 dB from reference [8].

Table 1. List of standard uncertainty for instrumentation of the SAM measurement.

Instrumentation	Uncertainty (dB)	Cal. Reference
signal generator	0.1	Mfr.
power meter/sensors	0.089	Internal
dc voltmeter	<0.001	Mfr.
spectrum analyzer	0.123	Internal

The power meter and sensors were compared to the calibrated type-IV power meter. The 2 percent repeatability of the power sensor measurements is combined with the 0.5 percent of the type-IV calibration by using eq (2). This gives a standard uncertainty of $10 \cdot \log(1+\sqrt{(0.02)^2+(0.005)^2}) = 0.089\,\text{dB}$ for the power meter and sensors.

According to the manufacturer in reference [9], the standard uncertainty of the DVM for dc voltage measurements is ≤ 0.01 percent. This converts to <0.001 dB.

The spectrum analyzer was also compared to the type-IV power meter and calibrated power sensor. Its average repeatability was 0.121 dB (see section 4.5) giving a standard uncertainty in these measurements of $\sqrt{(0.121)^2+(10 \cdot \log(1.005))^2} = 0.123\,\text{dB}$.

The standard uncertainties due to instrumentation calibrations are summarized in table 1.

4.1. rf-to-dc Transfer Function of the Standard Antenna

An rf-to-dc voltage transfer measurement (figure 1) is made for each measurement run on the OATS and has an associated uncertainty $u_{rf\text{-}dc}$. A study of the measurement will help determine its uncertainty.

Since the response of the Shottky diode depends upon temperature, the voltage transfer function is measured at temperatures within 10 °C of the external environment. This range caused negligible differences in the results.

Data are taken for dc voltages from 0.05 V to 2.5 V using the setup in figure 1. A linear fit is obtained for each set of data and this curve is then used to determine the open-circuit voltage from eq (1b). The correlation coefficient for the curve fit (*r* in reference [2, p. 180]) is greater than 0.995. The set of curves for each standard mount is analyzed for the maximum variation from curve to curve. Figure 3 shows a summary of the average and standard deviation of this variation expressed in decibels.

A histogram of these data is given in figure 4 using bins every 0.005 dB. The histogram shows that there is an offset in the data around 0.04 dB and that most of the data have little variation. For dc voltages between 0.25 V and 1.50 V, which are typical values used for SAM testing, the average variation is 0.047 ± 0.012 dB.

Associated with this measurement, from figure 1, are thermocouple power meter/sensors that have listed uncertainties of 0.089 dB, as reported in section 4.1. The other items from figure 1, losses of the directional

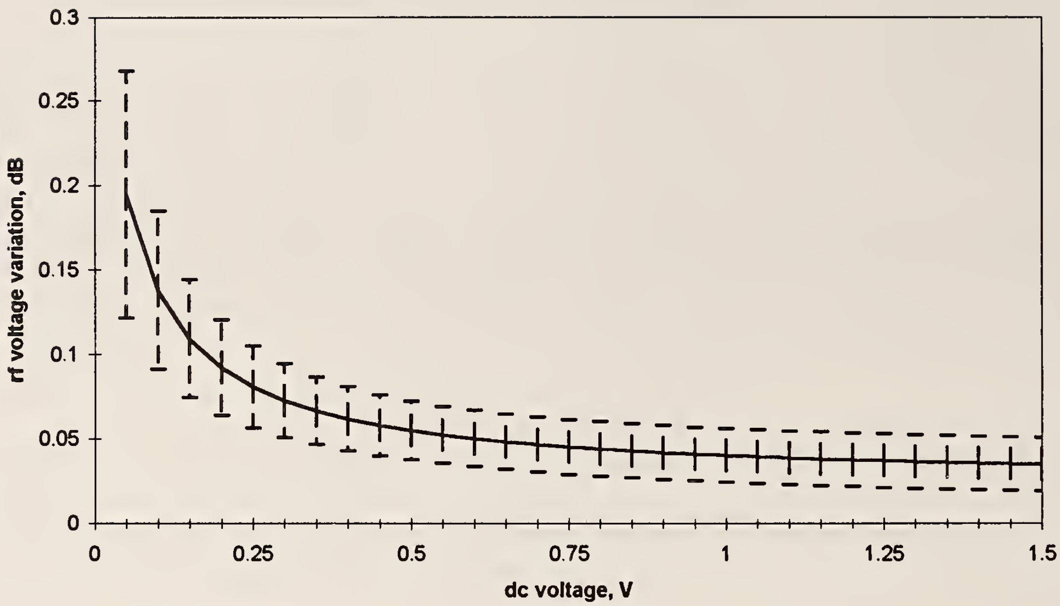

Figure 3. Variation due to data curve fit, rf-to-dc voltage transfer measurement.

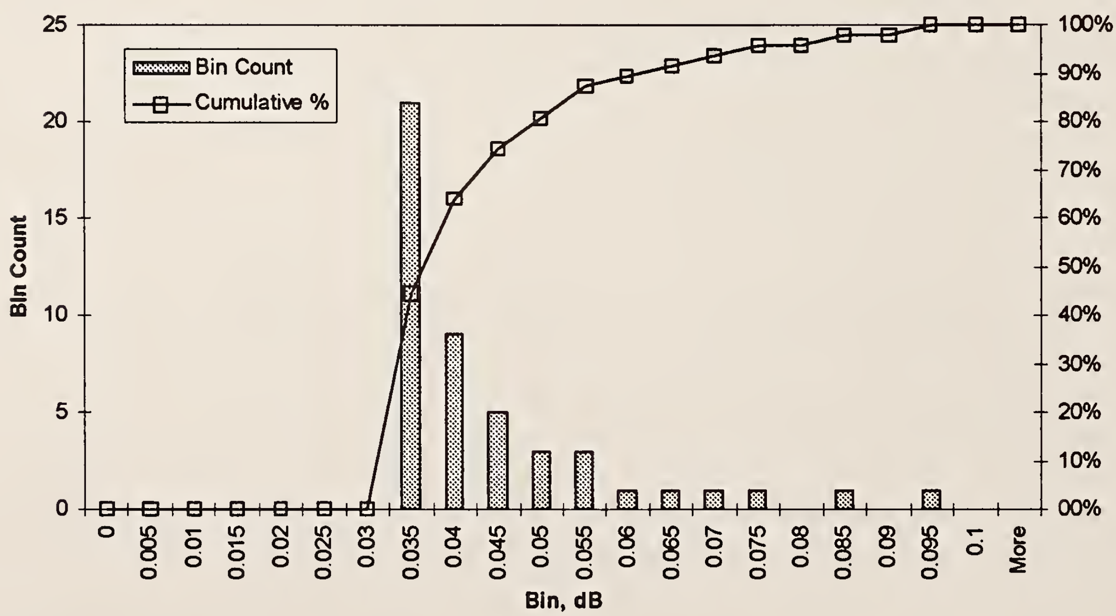

Figure 4. Histogram of average variation due to data fit, rf-to-dc voltage transfer measurement.

coupler and losses in the hybrid were also measured with a power meter/sensor having uncertainties of 0.089 dB, for each component. Combining these values as eq (2) suggests gives

$$u_{RF-DC} = \sqrt{(0.047)^2 + (0.089)^2 + 2\cdot(0.089)^2} = 0.161\,\mathrm{dB}.$$

4.2. Effective Length of the Standard Antenna

Determination of the effective length of the NIST standard antenna L_{eff} was recently addressed in reference [10]. Estimates of the change in the computed values of the effective length ∂L_{eff} were detailed for various setup configurations. The uncertainty for this term is defined as $u_{Leff} = 10 * \log(1 + \partial L_{eff} / L_{eff})$.

Figure 5 shows a summary of this uncertainty analysis that is reduced to an average value of u_{Leff} = 0.019 ± 0.011 dB. The histogram for this data is shown in figure 6 with bins every 0.001 dB. The histogram shows a bimodal shape where each peak is due to different setups of the antennas as detailed in reference [10]. Otherwise this graph shows a normal distribution of the data.

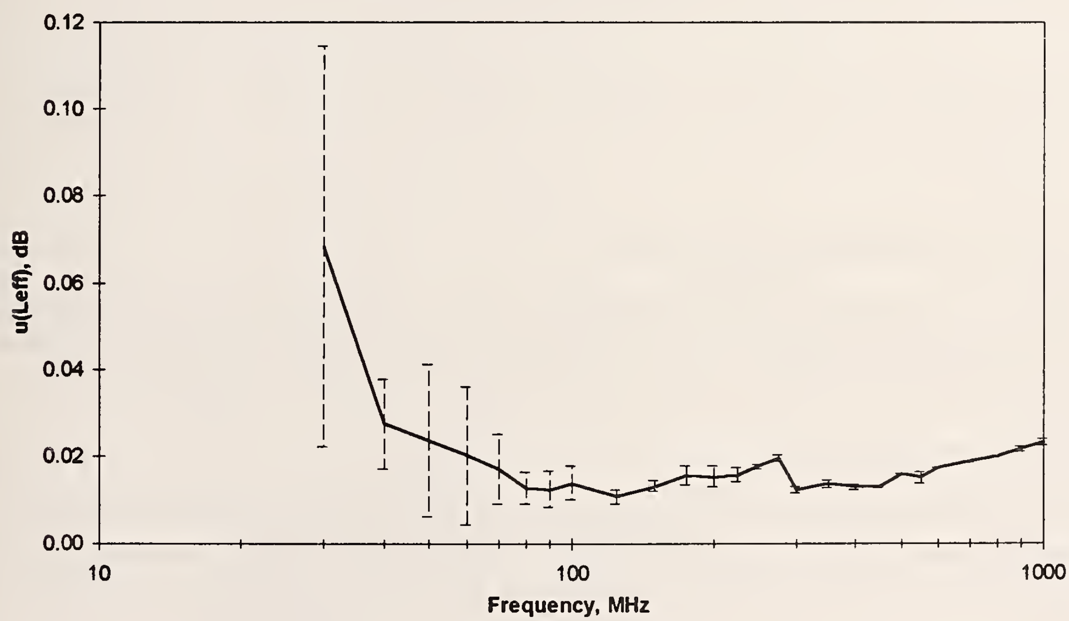

Figure 5. Average uncertainty of L_{eff} vs. frequency.

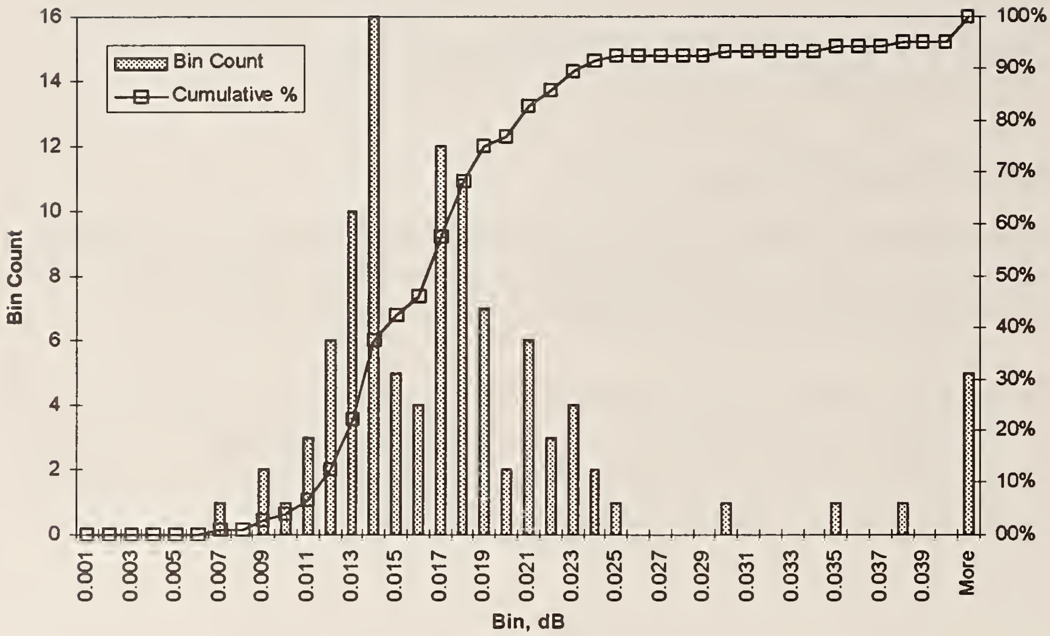

Figure 6. Histogram of L_{eff} uncertainties.

4.3. dc Voltage Measurement of the Standard Antenna

DC voltage measurements are the best controlled of any during an EMC measurement. From table 1, for dc voltage measurements, the uncertainty of the DVM is <0.001 dB. This value is below the round-off for the uncertainty of this test. As expected, this is a very small value and will be considered negligible.

4.4. rf Voltage Measurement of the AUT

The response of the AUT is measured with a spectrum analyzer. The spectrum analyzer is compared to a calibrated power sensor and meter for each reference level used. Reference levels for the spectrum analyzer varied from +5 dB (re 1 mW) to -20 dB (re 1 mW) every 5 dB (re 1 mW). This comparison is performed for every AUT.

Figure 7 shows the repeatability of these comparison measurements. Figure 8 is the histogram using 0.01 dB bins. The average repeatability is 0.121 ± 0.035 dB. This shape is also normal with some data trailing at the high end.

The power sensor and meter has an instrumentation uncertainty of 0.089 dB from table 1. Combining these values as eq (2) suggests gives $u_{RF} = \sqrt{(0.121)^2 + (0.089)^2} = 0.150\,\text{dB}$.

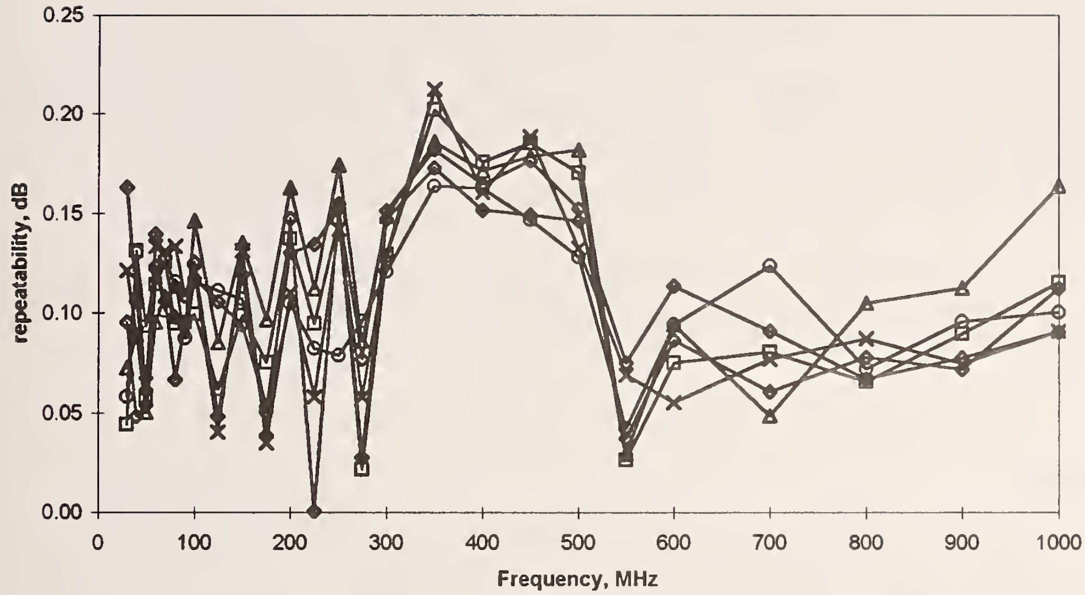

Figure 7. Repeatability of spectrum analyzer measurements over frequency.

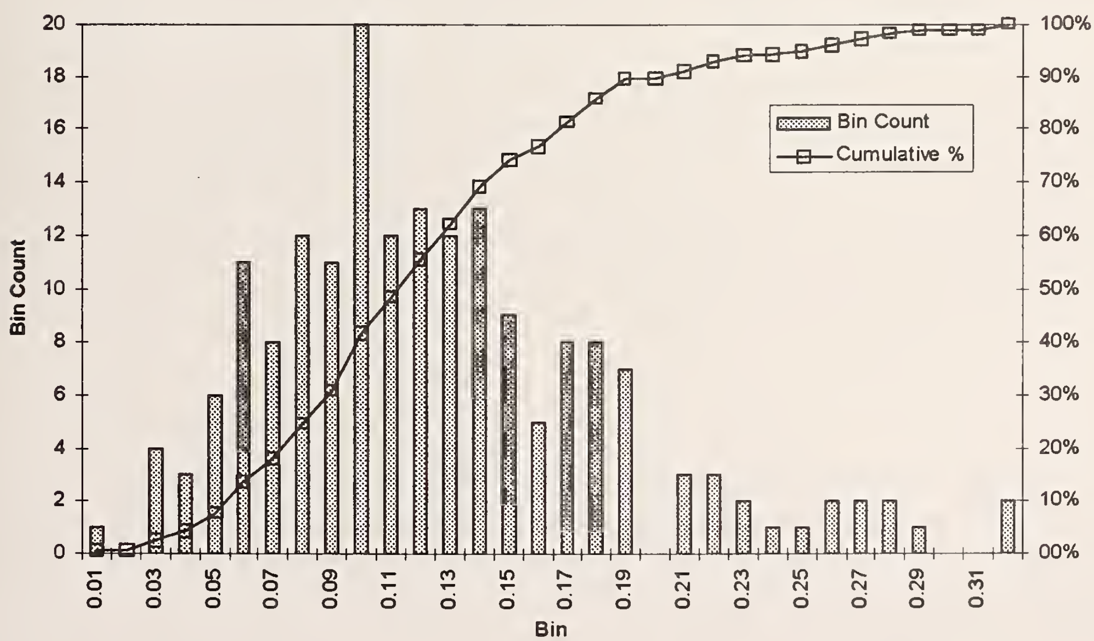

Figure 8. Histogram of spectrum analyzer repeatability.

4.5. Measurement of Loss in the Receiving Cable

The loss of the coaxial receiving cable was measured with a power meter and sensor, over the frequency of interest. The repeatability of these measurements is shown in figure 9. Figure 10 has the histogram for this data using bins of 0.005 dB. The average repeatability is 0.029 ± 0.019 dB. There are fewer data here than for the other terms; however, there is enough to determine the average value for this passive device.

This part of the uncertainty has two components, the repeatability of the measurement and the calibration of the equipment. The total uncertainty of this measurement, including the instrument calibrations from table 1, is $u_{cbl} = \sqrt{(0.029)^2 + (0.089)^2} = 0.094$ dB.

4.6. rf Source Stability

The rf source for SAM consists of a signal generator, an 80 W rf power amplifier, and a low-pass filter. The signal generator by itself has a very stable and repeatable rf output. However, the rf amplifier's output is dependent upon its warm-up time and the amount of drive into the unit. For this type of measurement, the amplifier is allowed to stabilize over 20 min and the input drive is only on long enough to take a steady reading. A reading is considered steady when the rf power monitor's reading is stable for a few seconds. Since the drift in the amplifier can be compensated with the output of the signal generator, this leaves only the resolution of the signal generator as a component for uncertainty. Therefore, from table 1, the uncertainty due to this component is $u_{source} = 0.1$ dB.

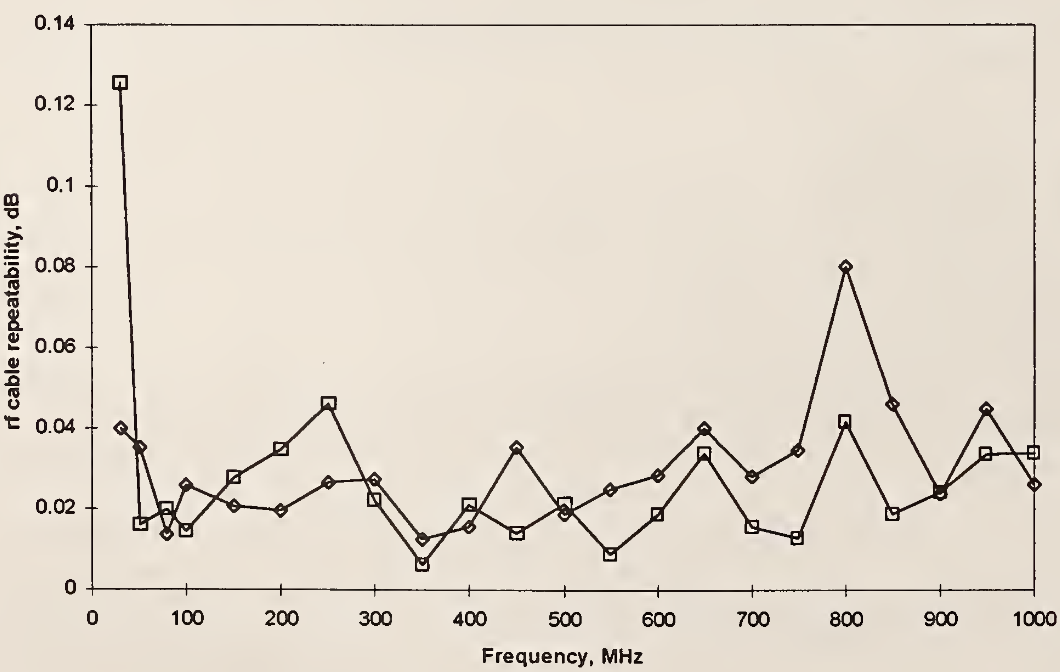

Figure 9. Repeatability of cable loss measurement.

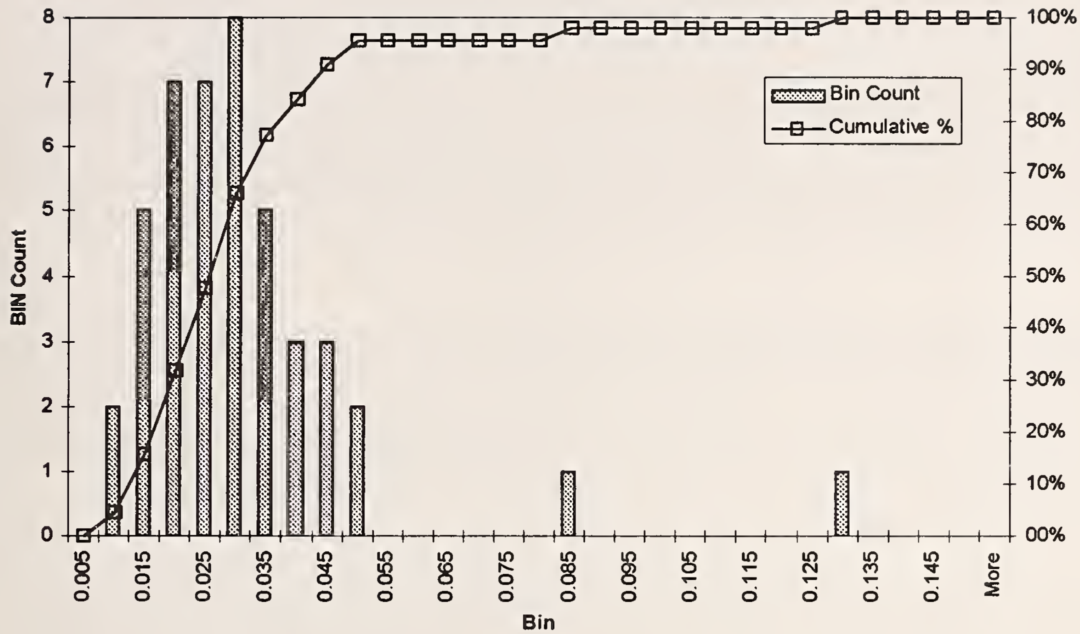

Figure 10. Histogram of cable loss repeatability.

4.7. Alignment of Antennas on OATS

The transmitting and receiving antennas are placed on tripods or on an EMC mast for measurement on the OATS. Position alignment includes the setting of height for each antenna and the spacing between antennas as well as the orientation of each antenna. Tripods are stationary and are used for fixed positions. The position and orientation of an antenna on a tripod is repeatable within 1 cm in each direction (height and separation distance). The EMC mast is a motor-controlled pulley system that is also repeatable within 1 cm in each direction. These positioning variations project changes in the E-field of $u_{align} = 0.08$ dB for two dipole antennas with typical separation distance of 10 m and antenna heights of 2 m.

4.8. E-field Uniformity

The characteristics of both receiving and transmitting antennas affect the formation of the E-field and are directly relevant to the combined standard uncertainty. Included in this term is each antenna's directivity, its height above the ground plane, radiation pattern and physical size. The directivity of the AUT will be dependent in part upon its environment; this term will be included in the resultant antenna factor. An increase in the alignment uncertainty due to variations in the directivity is estimated to be 0.1 dB. The radiation pattern is of concern when it differs from the standard dipole pattern, since the standard dipole is the reference object. Estimated uncertainties on the order of 0.15 dB can be expected. The size of the antenna dictates the spatial volume used for measurement of the E-field. So, a larger antenna requires an E-field that is uniform over a larger volume than is required for a small antenna. This adds another 0.15 dB of uncertainty due to the expected uniformity of the E-field over different volumes for typical EMI antennas. Combining these as described earlier, eq (2) gives $u_{ufm} = \sqrt{(0.10)^2 + (0.15)^2 + (0.15)^2} = 0.235$ dB.

4.9. Measurement Repeatability and E-field Environmental Interaction

This is the most difficult value to assess. It depends on the interaction of the transmitted E-field with the environment of the OATS; including intrusive time-varying ambient signals, reflection from nearby objects, and non-ideal reflection off the ground plane. All this is further dependent upon the frequency of interest. Ambient signals can be viewed only when the measurement signal is off. Use of narrow-band filters allows the rf receiver to bypass most intrusive signals. The diode detector on the standard antenna's response allows for a broadband response to be measured with the dc voltmeter.

At NIST, ambient signals are required to be less than or equal to 10 percent of the test signal, as measured with the standard antenna. Higher signal strength from the source allows for the ambient signal to be overwhelmed by the test signal. Sometimes, even this is not effective for large ambient signals on certain days and requires a change in the orientation of the setup to minimize the intrusive E-field. This extreme measure is necessary only at a few frequencies and is rarely needed. It is however, very effective to minimize the ambient signal, if directional.

Repeatability of measurements and use of check standard comparisons are standard components of SAM tests at NIST. AUTs are measured at least two independent times and the results compared. The check standard antennas are a set of broadband dipoles that are measured with every AUT. Results are compared to historical data to ensure continuity at the site.

Even though this repeatability incorporates some of the other components stated earlier, this should signify the uncertainty of the repeatability of the antenna under test and the condition of the OATS environment at its worst case. Repeatability of SAM tests at NIST is ≤0.25 dB for any one AUT. Check standard antenna repeatability is also ≤0.25 dB, based on its historical data. If we assume rectangular distribution for this repeatability, this relates to a standard uncertainty of $u_{rept} = 0.25/\sqrt{3} = 0.144$ dB.

5. Summary of Uncertainties

The individual standard uncertainties for this method are detailed in section 4 and summarized in table 2. This method employs a series of independent steps to arrive at the final outcome, the antenna factor of the AUT. Uncertainties are classified into two types: A and B from reference [2]. For type A uncertainties, each $u(x_i)$ is based on statistical data derived from previous measurements. For type B uncertainties, the $u(x_i)$ were determined from manufacturer's specifications or from engineering knowledge and experience. The combined standard uncertainty u_c is the root-sum-of-squares of each of these independent steps, as defined in eq (2).

To summarize the individual uncertainty components:

- The open-circuit voltage from a linear curve fit where the slope is known to within 0.5 percent.
- The standard antenna lengths are measured to within 0.1 percent.
- The dc voltage is considered exact.
- The receiver and cable uncertainties are based on repeated measurements using calibrated equipment.
- The rf source is allowed to stabilize.
- Antenna alignment is done with utmost care and precision, and a good tape measure.

- Repeat measurements assure any anomaly due to OATS interaction are discovered.
- Check standard antennas insure good repeat measurements.

The combined standard uncertainty for the SAM is obtained by using eq (2). Combining all the terms in table 2 gives

$$u_c = \sqrt{(0.161)^2 + (0.019)^2 + (0.150)^2 + (0.094)^2 + (0.10)^2 + (0.08)^2 + (0.235)^2 + (0.144)^2} \text{ dB} \qquad (4)$$

$u_c =$ 0.4 dB.

To obtain the expanded uncertainty U, we use a coverage factor as described in reference [2] of $k = 2$

giving $$U = k \cdot u_c \qquad (5)$$

or $U = 0.8$ dB.

Table 2. Standard antenna individual uncertainties.

Description	Variable	Type	Value (dB)
rf-to-dc transfer function of the standard antenna	$u_{rf\text{-}dc}$	A	0.161
effective length of the standard antenna	u_{Leff}	A	0.019
dc voltage measurement of the standard antenna	u_{dc}	B	neg.
rf voltage measurement of the AUT	u_{rf}	A	0.150
measurement of loss in the receiving cable	u_{cbl}	A	0.094
rf source stability	u_{source}	B	0.10
alignment of antennas on OATS	u_{align}	B	0.08
E-field uniformity	U_{ufm}	B	0.235
Measurement repeatability and E-field environmental interaction	U_{rept}	A	0.144

6. Conclusions

Most of the antenna calibration work for the EMC measurement industry at NIST has been with biconical, log-periodic, and tuned-dipole antennas. The antenna factor at frequencies between 30 and 1000 MHz is measured using the standard antenna method, which includes an uncertainty analysis needed for meaningful measurement results.

When uncertainties are assessed, the full sequence of measurements needs to be addressed and not just individual segments. This paper accurately presents the uncertainties for SAM measurements on the OATS. The largest individual uncertainty is in determining the antenna characteristics. This uncertainty will be present for any type of measurement procedure. The next two largest individual uncertainties are with the E-field transfer function of the standard antenna and the rf voltage measurement of the AUT. These three terms need to be reduced for any substantial reduction in the expanded uncertainty. These three terms will be further analyzed in future work.

Current guidelines for analysis of the uncertainty have been applied for determining antenna factor for an AUT at NIST. The results of this procedure yield an expanded uncertainty of 0.8 dB or a standard uncertainty of 0.4 dB.

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