Measurement Uncertainty in EMC

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Directions on how to calculate measurement uncertainty are presented, along with suggestions for its reduction.

INTRODUCTION

In 1993, CISPR Subcommittee A agreed on a project dealing with measurement uncertainty when determining compliance with a limit. In 1996, an amendment to CISPR 16-2 was drafted.[1] ETSI-Report ETR 028[2] requires a statement on measurement uncertainty in test reports. Additions to ETR 028 regarding EMC measurements are expected soon. A 1995 draft of the European Standard prEN 50 222[3] included a statement saying that the measurement uncertainty in EMC tests must be evaluated and must be made available on request. Thus, the topic of measurement uncertainty came to the attention of the international EMC world.

The need to calculate the amount of measurement uncertainty is not limited to Europe. With the required accreditation of EMC test labs in the USA,[4] Australia and New Zealand, there is a general international interest in EMC measurement uncertainty.

DEFINITIONS AND REQUIREMENTS

Until recently, accuracy requirements in EMC standards were limited to specifications for the maximum errors of test equipment and specifications for test setups and procedures. For example, in MIL-STD-461/462 the maximum error for the amplitude is 2 dB and for the frequency it is 2%. In CISPR 16-1[5] the maximum error for a sine wave voltage is 2 dB and for the field strength (of a plane wave) it is 3 dB. An awareness of problems with reproducibility of measurement results beyond the errors of instrumentation led to an analysis of the individual errors and to the adoption of the concept of measurement uncertainty in the field of commercial EMC testing. Basics of the analysis are given in the ISO Guide to the Expression of Uncertainty in Measurement,[6] which has been prepared by metrologists at national calibration institutes, and in other international and national standards.[7-9]

The first attempt to thoroughly explain measurement uncertainty in EMC is contained in a NAMAS publication.[9] A summary of the current situation is given in this article and others.[10] Readers should note that in this article, comparisons to a limit are made for cases involving emission measurements. They are similarly valid for immunity tests.

In the past, there was no official convention (i.e., not defined by standards) for treating measurement uncertainty in EMC tests, nor was this subject defined by any standard. Most users of EMC standards incorporated a margin of error several dB below the limits (for emission tests), and this margin of error took both measurement uncertainty and EUT variability into consideration. The early German standard VDE 0871/6.78 contained a procedure for single-unit type tests. For these cases, a safety margin of 2 dB was selected, i.e., the emission limit was reduced by 2 dB. In a type test with at least three samples of the EUT, the 80%/80% rule was applied without an additional safety margin. If, according to VDE 0871, a single appliance was used by an authority (market observer) for the verification of compliance with a limit, the appliance failed the test only if the limit was exceeded by more than 2 dB. Thus, the probability of conflicts between the authority and the manufacturer was reduced. Applying the limit was not done when the 80%/80% rule was used. Therefore, it is obvious that this safety margin has nothing to do with measurement uncertainty.

Current international and European standards do not require any safety margin, either for the single-unit type test or for the 80%/80% rule type test with three or more units (Figure 1).

Since in the past there was no margin for measurement uncertainty, prEN 50 222 postulates that "the limits and test levels in EMC product standards have been set taking into account typical measurement uncertainty contributions from test equipment and facilities while meeting the accuracy limits stated in the relevant basic standards."[3] This

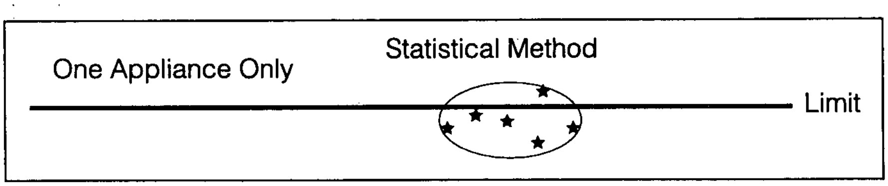

Figure 1. *In contrast to the former German standard, VDE 0871/6.78, current international product standards, e.g., CISPR 22, do not require a safety margin for the single-unit type test.*

postulate is a political statement: it cannot be found in any standard.[11] The opposite would be a margin of error in the amount of the uncertainty deviation from the limit. A margin of error from the existing limits would imply an unbearable aggravation of EMC product standards entailing an intolerable hardship for equipment manufacturers. The basis for prEN 50 222 is called the *concept of the shared risk*: equipment manufacturers and users each bear half of the risk of measurement uncertainty if the manufacturer does not provide any margin against the limit. In the case of radio disturbance, it is the public that bears the risk of a lower signal-to-interference ratio in radio reception due to measurement uncertainty.

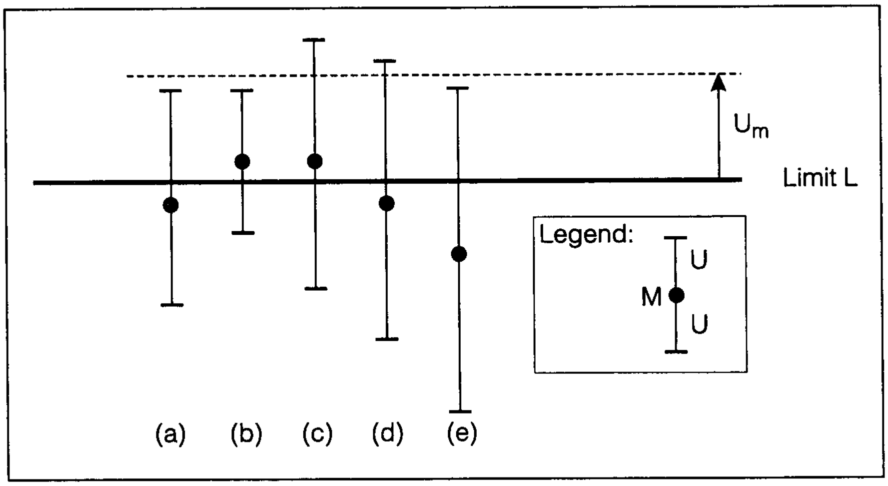

Figure 2. *According to all standards the EUT will fail the test in cases (B) and (C), whereas the EUT will meet the limit in cases (A) and (E). Critical is case (D). According to ETR 028 and the CISPR/A draft, the EUT fails the test. According to EN 50 222, the EUT meets the limit.*

Regarding the accuracy limits, prEN 50 222 refers to basic standards. However, these only specify error bounds of the instrumentation and not the complete test procedures. In that respect, ETR 028[2] and the draft of CISPR/A[1] are different from prEN 50 222. In ETR 028 and CISPR/A there is a limit to the measurement uncertainty of the complete test. An EUT passes when

$$M < L$$

and when

$$M + U < L + U_m$$

where

M = measurement result
L = limit
U = actual measurement uncertainty at a level of confidence of 95%
U_m = maximum measurement uncertainty

The manufacturer has to consider a margin of error from the limit if the measurement uncertainty of the EMC lab is above the maximum uncertainty U_m. For the reader's orientation, values of U_m intended in ETR 028 and given in various ETS are 3 dB for conducted emissions and 6 dB for radiated emissions.

A manufacturer is, of course, always advised to develop equipment so that there is a sufficient safety margin between the test result and the limit in a single-unit test in order to assure that variations in production and variations due to imperfect reproducibility of the test do not cause problems later.

CALCULATING MEASUREMENT UNCERTAINTY

An EMC test result without an expression of measurement uncertainty at a given level of confidence is of little value. Therefore, specially accredited EMC test laboratories should report these data. (The obligation to report may be dropped in the final version of EN 50 222.) Basics for the calculation of measurement uncertainty are contained in several sources.[6-10]

Measurement uncertainty is caused by random effects and imperfect correction of systematic effects. The first step for its determination is a list of all possible factors which contribute to uncertainty. The values may depend on the amplitude or frequency range. Therefore, range-dependant values may be appropriate in some cases. If limits and test results are predominantly given in logarithmic quantities, e.g., in dB(μV) or dB(μV/m), then the measurement uncertainty should also be given as logarithmic values (in dB). However, if they are given in absolute quantities, e.g., in V or V/m, then the measurement uncertainty should be given in percentages.

For an evaluation of the total uncertainty, the *standard uncertainties* of the individual components are first determined. From them, the *combined standard uncertainty* can be calculated, and with the coverage factor the *expanded standard uncertainty* can be calculated.

Depending on the method of evaluation, there is a Type A evaluation method and a Type B evaluation method. According to NAMAS, all individual components can be associated with one of three distribution functions: normal (Gaussian), rectangular or U-shaped.[9]

The Type A evaluation method assumes normal distribution and uses statistical procedures in order to compute the statistical parameters mean and standard deviation from a sufficient number of readings of the measurand. From n measurements q_k of the input quantity q, the standard deviation of the mean $s(\bar{q})$ and the standard deviation of the sample $s(q_k)$ are computed:

$$u(x_i) = s(\bar{q}) = \frac{s(q_k)}{\sqrt{n}} \quad (1)$$

$$s(q_k) = \sqrt{\frac{\Sigma(q_k - \bar{q})^2}{n - 1}} \quad (2)$$

The standard uncertainty $u(x_i)$ of an estimate x_i of the input quantity q, based on the Type A evaluation is equal to $s(\bar{q})$, as written in Reference 1.

However, the Type A evaluation method should not be understood as the determination of the *total* uncertainty of conducted or radiated disturbance by repeated measurement of a signal at one frequency. This would instead serve for the determination of the statistical parameters of one individual uncertainty contribution (e.g., the variability of the signal to be measured vs. time). Also, the measurement uncertainty of a measuring receiver cannot be determined from a number of readings of a signal at one frequency. Three factors determine the uncertainty of a measuring receiver with built-in calibration:

- Frequency response of the internal calibration source
- Error of the built-in step attenuator
- Nonlinearity of the detector[12]

To determine the uncertainty of a receiver as a whole, exactly defined (reference) values of signals in the level and frequency range of interest would have to be used to determine the individual deviations between measured values and reference values.

Instead of that, manufacturers' data are used for most measuring equipment in order to determine standard uncertainty according to the Type B evaluation method as described by NAMAS[9] and others.[10] If the manufacturer specifies maximum deviations of ±e% or ±e dB and does not specify the level of confidence, then a rectangular distribution may be assumed according to NAMAS. In other words, the probability distribution between e_- and e_+ around the mean value is constant. From this, Equations (3) and (4) are derived:

$$u(x_i) = \frac{e_+ - e_-}{2\sqrt{3}} \tag{3}$$

and if $|e_+| = |e_-|$, as in the case of ±e%, then

$$u(x_i) = \frac{e}{\sqrt{3}} \tag{4}$$

Of course, in the case of a measuring receiver the distribution of measurement errors is not rectangular; it is normal. If the level of confidence is 95% (k=2), then $u(x_i) = e/2$. If the level of confidence is 99.7% (k=3), then $u(x_i) = e/3$. It is obvious that Equation (4) gives a higher value for the standard uncertainty. Manufacturers of test equipment have to fulfill IEC 359.[13] In other words, when testing the measurement uncertainty of an instrument, the manufacturer has to incorporate a safety margin in the amount of measurement uncertainty of the test equipment below the guaranteed error limit of the instrument under test. Therefore, the guaranteed maximum error is practically never reached or exceeded.

According to NAMAS, mismatch errors caused by VSWR, e.g., at the intersection between antenna output and measuring receiver input, have a U-shaped distribution. In this case, the uncertainty *e* caused by mismatch is:

$$e = 20Log_{10}(1-|\Gamma_a||\Gamma_r|)$$

where

Γ_a and Γ_r = reflection coefficients of antenna and receiver.

In this case, the standard uncertainty is:

$$u(x_i) = \frac{e_+ - e_-}{2\sqrt{2}} \tag{5}$$

and, if *e* is the maximum of the two values:

$$u(x_i) = \frac{e}{\sqrt{2}} \tag{6}$$

The combined standard uncertainty $u_c(y)$ of a quantity y can be computed from the standard uncertainties $u(x_i)$ of the individual components by evaluating the square root of the sum of the squares (RSS). If the quantity of an individual component does not correspond with that of the measurand (the quantity being measured) e.g., the effect of measurement distance uncertainty on measured field strength, then it has to be converted first by

$$u_i(y) = c_i \cdot u(x_i)$$

For m individual components

$$u_c(y) = \sqrt{\sum_{i=1}^{m} u_i^2(y)} \tag{7}$$

This form of computation is valid for uncorrelated individual components, which are the most common.

For the expanded measurement uncertainty U the combined standard uncertainty is to be multiplied by the coverage factor k:

$$U = k \cdot u_c(y) \tag{8}$$

The coverage factor determines the level of confidence. For the recommended level of confidence, 95%, k = 2.

AN EXAMPLE OF UNCERTAINTY COMPUTATION

Examples of measurement uncertainty computation for emission measurements may be found in several sources.[9-10] Examples of tests for immunity against radiated emissions are also available in the literature.[9, 14]

For conducted emission measurements, the calibration of the voltage division factor of the LISN is an essential factor for improving measurement uncertainty. Such a calibration can be performed following ANSI C63.4/1992. A corresponding amendment to CISPR 16-1 is under preparation. Due to space considerations, conducted emission tests cannot be further treated here.

Table 1 contains an example of an uncertainty computation for radiated emission tests at a measurement distance of 10 m. For comparison, the presentation table offered in two sources has been chosen.[9-10] The biconical antenna is

Aspect of Measurement Uncertainty	Probability Density Distribution	Uncertainty/dB Biconical Antenna	Uncertainty/dB Log-periodic Antenna
Antenna factor (Free space calibration)	normal (k=2)	±1.0	±1.0
Antenna cable calibration	normal (k=2)	±0.2	±0.5
Measuring receiver specification	rectangular	±1.0	±1.0
Antenna factor variation with height	normal (k=2)	±1.0	±0.2
Antenna directivity	rectangular	hor/vert: 0/+0.2	+0.2/+0.5
Antenna phase center variation	rectangular	0	±0.3
Measurement distance variation	rectangular	±0.5	±0.5
Antenna factor interpolation vs. frequency	normal (k=2)	±0.2	±0.1
Site imperfections	rectangular	±2.0	±2.0
Mismatch (VSWR) Receiver: $\Gamma = 0.2$ Biconical-A: $\Gamma_a = 0.67$ LPA: $\Gamma_a = 0.3$ Uncertainty limits: 20 Log $(1 \pm \Gamma_r\Gamma_a)$	U-shaped	+1.1 -1.25	±0.5
Signal-to-noise ratio 10 ... 20 dB	rectangular	-0.5	-1.0
System repeatability	Standard deviation	±0.5	±0.5
Combined standard uncertainty	normal	1.79	1.70
Expanded measurement uncertainty	normal (k=2)	3.58	3.40

Table 1. *Uncertainty for Radiated Emissions Test at 10 m.*

used in the frequency range of 30 to 200 MHz, whereas for the log-periodic antenna the range is 200 to 1000 MHz. For signal-to-noise considerations, the limits of CISPR 22, Class B have been chosen.

Combined standard uncertainty for the case of the biconical antennas:

$$u_c(y) = \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{0.2}{2}\right)^2 + \left(\frac{1}{2}\right)^2 + \left(\frac{0.2}{2}\right)^2 + \frac{1^2+0.2^2+0^2+0.5^2+2^2+0.5^2}{3} + \frac{1.1^2}{2} + 0.5^2} = 1.79 \text{ dB}$$

REDUCING UNCERTAINTY

Antenna factor. It is important to have a good approximation of the free-space antenna factor, because it is the best average of all mutual coupling influences (with the ground plane, etc.), thus minimizing the overall uncertainty contribution of the antenna factor.

Antenna cable calibration. For minimum uncertainty the use of a network analyzer is recommended. The temperature influence when used on an OATS should be taken into consideration. Low loss cables will cause lower uncertainty and a better uncertainty budget due to a better signal-to-noise ratio.

Measuring receiver specification. Measuring receivers with low values of uncertainty are commercially available.[12]

Antenna factor height variation. Due to mutual coupling with the ground plane, antenna factors, especially of biconical antennas, vary with antenna height. Biconical antenna types differ in their antenna factor height variations. Unfortunately, this is not specified by manufacturers. The values given in Table 1 are achievable.

Antenna directivity. This parameter is important especially with log-periodic antennas in vertical polarization and for close distances (e.g., 3 m). Tilting the antenna down minimizes uncertainty.[15] The antenna should, however, not be tilted bore-sight to the EUT but into the half angle between direct and reflected rays.

Antenna phase center variation. This effect, which occurs with log-periodic antennas, will increase with the reduction of measurement distance and with the increasing bandwidth of the antenna.

Measurement distance variation. This applies to the position of the EUT center of radiation, which changes according to the turntable position.

Antenna factor interpolation. It is obvious from Table 1 that the influence on the total uncertainty budget is small.

Site imperfections. The value given in Table 1 is an estimate. It largely determines the uncertainty budget. The value should be determined by comparison with a precision reference test site. This is especially necessary for semi-anechoic chambers.

Mismatch. The influence of the high reflection coefficient of biconical antennas is considerable.

Signal-to-noise ratio. The values in the table correspond with those of a good receiver for the limits of CISPR 22. According to the definition (see sidebar) the error introduced by the receiver's inherent noise is partially due to a systematic effect, which can be compensated for only if the signal type to be measured is known. Its dependance on signal type and signal-to-noise ratio is shown in Figure 3. It is important to use high sensitivity receivers. The use of external preamplifiers will result in better sensitivity but may cause overload with signal compression and generation of intermodulations and harmonics, which can create serious measurement errors. In addition, external preamplifiers are not included in the receiver autocalibration routines.

CONCLUSION

This article deals with measurement uncertainty, the reduction of which is an essential precursor to achieving good reproducibility of EMC measurements. New standards are aimed at improving test lab performance. The repeatability of EUTs is not regarded here since it is not in the hands of the EMC test technician. To improve reproducibility, many details have to be considered. All factors contributing to measurement uncertainty have to be listed and evaluated. Not all details are treated in this article, but they should be addressed and include setting sufficient measurement times in emission measurements. Also not part of this article, but necessary for better reproducibility, are the test setup descriptions in EMI standards, which can also be improved with more specificity.

REFERENCES

1. Draft CISPR/A/ /CD/6.96 Proposal for Amendment of CISPR 16.
2. ETSI Technical Report ETR 028/3.94: Radio Equipment and Systems (RES); Uncertainties in the Measurement of Mobile Radio Equipment Characteristics.
3. Final Draft prEN 50 222/9.95: Standard for the Evaluation of Measurement Results Taking Measurement Uncertainty into Account.
4. FCC Report and Order in ET Docket No. 95-19, May 9, 1996, Amending Parts 2 and 15 of the FCC Rules. See also: J.P. Knapp, and A. Wall, " Streamlining the FCC Equipment Authorization Process in Response to Changing Global Markets," Proceedings of the 1996 IEEE EMC Symposium, Santa Clara, CA.
5. CISPR 16-1/8.1993: Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods.
6. ISO Guide to the Expression of Uncertainty in Measurement, 1st edition, 1995.
7. West European Calibration Coordination (WECC) Doc. 19-1990: Guidelines for the Expression of the Uncertainty of Measurement in Calibrations.
8. NIST Technical Note 1297, 1994 Edition: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.
9. NIS 81 Edition 1, May 1994: The Treatment of Uncertainty in EMC Measurements. NAMAS (British Accreditation Body).
10. E. L. Bronaugh and J. D. M Osburn, "A Process for the Analysis of the Physics

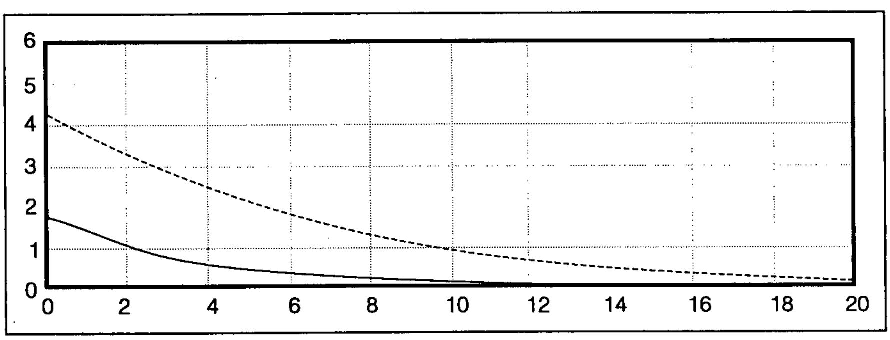

Figure 3. *Deviation of the QP detector reading in dB for a sine wave (dashed line) and a 100-Hz impulsive signal (full line) by superposition with the receiver's inherent noise. x axis: (S-N)/dB.*

DEFINITIONS[6]

Uncertainty (of measurement):
Parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Standard uncertainty:
Uncertainty of the result of a measurement expressed as a standard deviation.

Type A evaluation (of uncertainty):
Method of evaluation of uncertainty by the statistical analysis of a series of observations.

Type B evaluation (of uncertainty):
Method of evaluation of uncertainty by means other than the statistical analysis of a series of observations.

Combined standard uncertainty:
Standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities. It is equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.

Expanded uncertainty:
Quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand. Note: the fraction may be viewed as the coverage probability or level of confidence of the interval.

Error of measurement:
Result of a measurement minus the true value of the measurand.

Random error:
Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.

Systematic error:
Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus the true value of the measurand.

Repeatability (of results of measurements):
Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement (the repeatability conditions include the same measurement procedure, observer, measuring instrument used under the same conditions, location, and repetition within a short period of time).

Reproducibility (of results of measurements):
Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. (The changed conditions may include principle and method of measurement, observer, measuring instrument, reference standard, location, and conditions of use and time.)

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