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EMC MANAGEMENT: HOW TO COMPARE ELECTROMAGNETIC ENVIRONMENTAL MEASUREMENTS AND EQUIPMENT IMMUNITY LEVELS

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Abstract—The straightforward comparison between electromagnetic environment measurements and immunity levels for industrial, scientific, and medical equipment has been used in the technical literature as an ordinary method to provide electromagnetic compatibility management within critical areas, such as hospital and industrial environments. This paper addresses a theoretical discussion concerning emission and immunity test features to focus the aforementioned problem. Finally, a more reliable comparison method is proposed, the environmental compatibility level definition, using analytical analysis and measurement results.

1. INTRODUCTION

Advances in electronics technology, with a number of new developments in this area, have led to a gradual increase in the electromagnetic fields emitted to the environment. In addition, the fast proliferation of digital signal processing applications and a concomitant increase of electromagnetic disturbances over a wide spectrum, means that electromagnetic compatibility (EMC) remains an important source of concern.

Nowadays, it is possible to observe that only the basic EMC concepts (emission control and immunity levels) are not enough to guarantee the proper operation of equipment in some critical areas, since the environmental content where industrial, scientific, and

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medical (ISM) equipment are installed must be compatible to its operation as well. This situation can be of special interest in areas with a large number of equipment working simultaneously within a confined space (e.g., hospital and industrial environments), or with new technologies applications such as wireless local area networks, digital TV, paging, and mobile communication systems.

For this reason, it is shown in the technical literature a number of works whose main aim is to evaluate potentially hazardous electromagnetic environments. These works usually present an approach based in the use of measurement techniques in order to define the worst-case situation presented within the environment under test. The central idea is quite simple and consists of comparing the environmental worst-case situation with the immunity levels in which electrical equipment were projected to operate.

As a rule, this approach seems to be the consensus among the technical literature in this field of research. For instance, a number of important papers regarding this scope can be listed here for hospital environment assessments [1–9]. Most of them usually compare environmental measurements with the immunity levels (3 or 10 V/m) prescribed for electromedical equipment according to IEC 60601-1-2 (EMC collateral standard). However, this comparison needs to be carried out in a careful manner in order to truly represent the intended objective, and avoid incorrect or overly conservative approaches. This argument is the main focus of this work.

In the next sections, a theoretical review concerning this type of EMC testing is given, and practical measurements are performed in order to prove and define evidence for a more reliable method to provide comparisons for EMC environmental management.

2. ENVIRONMENTAL COMPATIBILITY LEVEL DEFINITION

As previously mentioned, a straightforward comparison of electromagnetic environment measurements and immunity levels for electro-electronic equipment has been used in the technical literature as a usual method to provide EMC management within critical areas [1–9]. However, it is possible to show that this approach may lead to wrong or overly conservative results.

The main mistake consists in using immunity levels presented by Table 1 as a reference, since these are not the real signals in which electrical and electronic equipment are exposed during radiated immunity tests. One should note that, for equipment testing, this signal is 80% amplitude modulated with a 1 kHz sinewave to simulate actual threats [10]. There are significant differences between the effects of diverse modulation types, but sine wave AM was defined in this standard because it presents the most severe disturbances observed [10]. It is also important to observe that immunity tests are related to RMS values, whereas electromagnetic environmental measurements usually employ quasi-peak or peak detectors. All these aspects should be considered in order to provide a consistent comparison method, unlike the straightforward comparison normally used up until now. In fact, it is easy to see that if a typical environment measurement setup (Fig. 1) is submitted to an immunity test (Fig. 2), results will be higher than those of Table 1 (as will be shown later in Section 4).

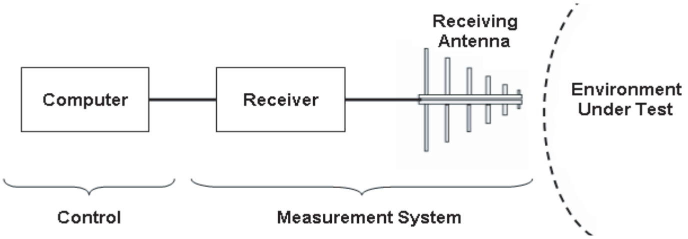

Figure 1. Typical setup for environmental measurement tests.

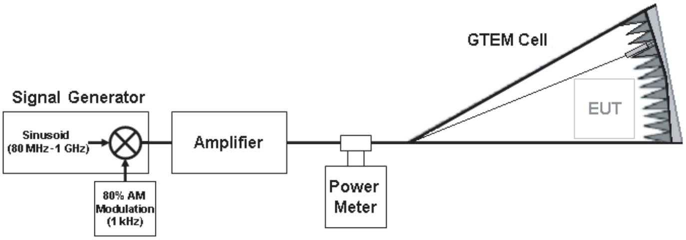

Figure 2. Typical setup for an immunity test.

Of course this result can also be analytically calculated. For instance, let be the wave shape prescribed by [10]. The unmodulated RF-signal $x(t)$ is a sinusoidal carrier (80 MHz to 1 GHz) wave given by (1):

$$x(t) = A\sqrt{2} \cdot \sin(\omega_x t). \tag{1}$$

The A constant is the RMS test field strength in V/m, and can be taken from Table 1 in agreement with the desired immunity level. During an immunity test procedure, the $x(t)$ signal is modulated by

Table 1. Immunity reference levels (80 MHz–1 GHz) [10].

Level	Test Field Strength (V/m)
1	1
2	3
3	10

a sinusoidal 1 kHz wave [$m(t) = \cos(\omega_m t)$], resulting in a RF signal $y(t)$ 80% AM, as expressed in (2) (where μ is the modulation index, $\mu = 0.8$):

$$y(t) = A\sqrt{2} \cdot [1 + \mu \cdot \cos(\omega_m t)] \cdot \sin(\omega_x t). \tag{2}$$

The IEC 61000-4-3 standard defines the maximum RMS value as the highest short-term RMS value of a modulated RF signal during an observation time of one modulation period [10]. Equations (3) and (4) are respectively the maximum RMS and wave-peak results for the modulated RF signal (E_y):

$$E_{y(maximum\_rms)} = A(1 + \mu) = 1.80A \text{ V/m}, \tag{3}$$

$$E_{y(peak)} = A\sqrt{2}(1 + \mu) = 1.80A\sqrt{2} \quad \text{V/m}. \tag{4}$$

According to the RMS definition, $E_{y(rms)}$ is given by (5).

$$E_{y(rms)} = \sqrt{\frac{1}{T}\int_0^T [y(t)]^2\, dt} = 1.12A \text{ V/m}. \tag{5}$$

Finally, Table 2 summarizes the results obtained with (1) to (5). It proposes a new term definition for environmental measurement problems named environmental compatibility level (ECL). ECL is defined as the maximum electric field presented within an environment that complies essential equipment performance according to its immunity level. So, it establishes an appropriate interface between an equipment immunity level and the environmental conditions in which this equipment is operating.

The use of ECL is an important way to provide EMC management in critical electromagnetic environments. For instance, if an environmental measurement result was higher than the ECL limits, the environment under test might be non-compatible to the proper equipment operation and EMI may appear. On the other hand, if an environmental measurement result was lower than the ECL limits, the environment would be compatible for equipment operation (because they were exposed to worse conditions during immunity tests).

Table 2. Environmental compatibility level (ECL) (80 MHz–1 GHz).

Level	A	$y(t)$ — Reference Field Strength (V/m) RMS	Maximum RMS	Wave-peak
1	1	1.12	1.80	2.55
2	3	3.36	5.40	7.64
3	10	11.2	18.0	25.5

It is important to note that ECL can be defined for both peak and RMS detectors depending on the environmental measurement test objective. Peak and maximum RMS are basically related to short-term EMI noise with high energy content, whereas the RMS value is basically related to a continuous EMI noise pattern during a long-term exposure. A further point is that ECL values (Table 2) present a well-defined correlation with immunity reference levels (Table 1). In fact, they can be converted to each other using a simple multiplicative factor.

3. MATERIALS AND MEHTODS

A test method was developed in order to check for ECL results consistency. All systems used in this assessment, as well as the test procedures and uncertainty estimates, are fully described here.

3.1. Equipment and Systems

This subsection describes all equipment and systems used in order to implement the current assessment, both the immunity test system and the environmental measurement system. It is important to mention that all equipment and systems employed during this analysis were tested in the facilities of an accredited EMC lab (MagLab/UFSC), in order to assure an adequate traceability to the National Metrology Institute.

3.1.1. Immunity Test System

The test system used during this assessment consists of 4 equipment modules according to the immunity test requirements [10], such as: a signal generator (SML-03 — Rohde & Schwarz), a power amplifier

(BLWA-0120-2/10D — Bonn Elektronik), a power meter (NRVD — Rohde & Schwarz), and a GTEM cell (5411 — ETS Lindgren).

3.1.2. Environmental Measurement Systems

The environmental measurement setup used during this analysis was a portable system consisting of a receiver/spectrum analyzer (FSH-3 — Rohde & Schwarz) controlled by a laptop with FSH View software. It presents a valid calibration certificate in order to assure results traceability. During the tests, the receiver was connected via double-shielded coaxial cables to a set of broadband antennas (HE-200 — Rohde & Schwarz). All measurements performed were narrow band and can evaluate emissions in a frequency range from 80 MHz to 1 GHz, according to the standard definition [10]. Typical instrumentation parameters [11] were used in order to configure the system setup.

3.2. Test Procedures

The test method basically consists of exposing a typical environmental measurement system (Fig. 1) to an immunity test setup (Fig. 2). This test procedure is divided in to 4 steps as follows:

Setting correction factors of the measurement system: This step consists in measuring all possible path losses of the environmental measurement system, such as cables and connectors, and checking for consistency of antenna factors due to its coupling features. These aspects were carefully defined in order to establish a set of correction factors as functions of frequency, according to manufacturer's data and the loss measurements taken.

Field calibration inside the GTEM cell: The purpose of the field calibration is to ensure that the uniformity of the field over the test sample is sufficient to guarantee the validity of the test results. Modulation is not present during the calibration to ensure a proper reading of any field sensor [10]. The intensity of the established field strength is checked by placing the field sensor at a calibration grid point; the forward power needed to give the calibrated field strength can be measured [10]. In this paper, Level 2 was chosen in order to demonstrate the current procedure. Therefore, a 3 V/m RMS, vertically polarization, non-modulated RF field was used during the calibration step.

Generating the RF immunity test field and measuring it: After the calibration has been verified, the test field can be generated using the power values obtained from the calibration. The frequency ranges to be considered (80 MHz to 1 GHz) are swept with the signal 80% amplitude modulated with a 1 kHz sinewave, pausing

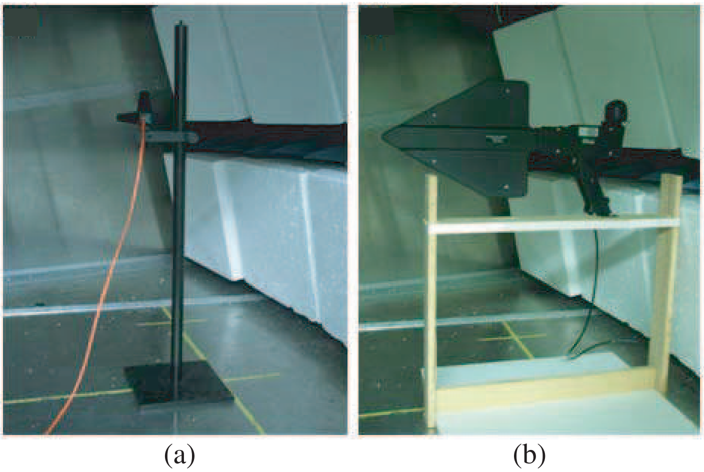

Figure 3. Inside view of GTEM cell: (a) Calibration field probe; (b) Receiving antenna.

to change the antenna module as necessary [10]. During this step, only the receiving antenna of the environmental measurement system was located inside the test area (within GTEM cell). It is also important to keep the receiving antenna in the vertical polarization at the same position as used for the calibration setup (see Fig. 3).

Test documentation and error analysis: During the ongoing procedure all measurement data were stored in the control computer for subsequent analysis and error calculation. The error term defined here is related to results variation or differences between measurement behaviors and the ECL expectations (see Table 2).

3.3. Uncertainty Estimation

Considering this paper deals with a measurement proof, it is important to obtain an estimate of the uncertainty associated with all measurement results. Uncertainty (of measurement) is defined as *"the parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurands"* [12]. The uncertainty estimate was developed for the measurement system setup according to a specific guide regarding this scope [12]. The basic methodology requires that the influence of each component of uncertainty on the measurement result be quantified and expressed numerically as a standard deviation (also named standard uncertainty). These values are then processed according to the rules of the propagation of uncertainty to produce a combined standard deviation (combined standard uncertainty) and the combined standard uncertainty is multiplied by a coverage factor to produce an expanded uncertainty at the required level of confidence.

Six main sources (factors of uncertainty) were identified in order to realize this estimate, such as signal source deviation, cable and connector losses, receiver accuracy, impedance mismatch (VSWR-antenna/receiver), unified field area (perpendicular plane), and longitudinal plane (receiving antenna plane). Uncertainty values and probability distribution models consist of a Type B evaluation, since standard uncertainty is estimated using data provided on calibration certificates and procedures, assumed probability distributions, laboratory records, and technical data from manufacturers manuals.

Uncertainty values and probability distribution models adopted for the measurement system employed in this work are presented in Table 3. Using standard uncertainty $u(x_i)$ provided this table it is possible to perform a suitable development in order to calculate the combined standard uncertainty u_c. It is evaluated according to (6):

$$u_c = \sqrt{\sum_{i=1}^{N} (c_i \cdot u(x_i))^2}. \tag{6}$$

where N is the total number of uncertainty sources (factors of uncertainty), and c_i is the sensitivity coefficient. This coefficient defines the mathematical relationship between an influencing parameter and its effect on the result of a measurement. In this analysis it is unity, which means a one to one relationship between the value of each uncertainty source and its effect on the measurement result [12]. Therefore, the combined standard uncertainty u_c for the measurement system employed in this work is $u_c = 0.89\,\mathrm{dB}$ (FSH-3 portable system).

The combined standard uncertainty u_c can be used to express the uncertainty of a measurement result, since it is the final estimate of uncertainty for the test or measurement result expressed as a standard deviation. On the other hand, it is also usual to express the uncertainty for a test result in terms of a confidence interval. The additional information which satisfies this requirement is called expanded uncertainty (Up). Expanded uncertainty is defined as *"the 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 measurands"*. It is calculated by multiplying the combined standard uncertainty by a coverage factor k_p to produce the desired level of confidence p, according to (7) [12]:

$$U_p = k_p \cdot u_c. \tag{7}$$

Table 3. Uncertainty estimative for measurement test system.

Uncertainty Source (x_i)	Value +/− (dB)	Probability Distribution	Divisor	Standard Uncertainty $u(x_i)$ (dB)
Signal Source	0,50	Rectangular	$\sqrt{3}$	0,29
Cables/Connectors Losses	0,36	Normal	2	0,18
FSH-3 Accuracy	0,50	Rectangular	$\sqrt{3}$	0,29
Impedance Mismatching	0,78	U-Form	$\sqrt{2}$	0,55
Unified Field Area (UFA)	0,93	Normal	2	0.47
Longitudinal Plane	0,54	Normal	2	0.27

Uncertainty of measurement is usually given as a 95% confidence interval ($p = 95\%$). As long as uncertainty sources in this analysis are Type B, the effective degrees of freedom tend to infinite and the coverage factor for a 95% confidence interval is $k_p = 2$ [12]. Therefore, the expanded uncertainty for a 95% confidence interval ($U_{95\%}$) of measurement system employed in this work is $U_{95\%} = 1.8\,\text{dB}$. So, it is in compliance with standards requirements, since it requires accuracy better than 3 dB [11].

4. RESULTS

With regard to field measurements tests, the incident electric field (E_{inc}) is usually expressed in logarithmic units such as dBµV/m. Since Level 2 was used during the test, an immunity level of 3 V/m *RMS* is represented by 129.5 dBµV/m (Table 1). Level 2 of ECL values for *wave-peak*, *maximum RMS,* and *RMS* (Table 2) are respectively 7.64 V/m (137.7 dBµV/m), 5.40 V/m (134.6 dBµV/m) and 3.36 V/m (130.5 dBµV/m).

Analytical error results were estimated using a frequency step of 40 MHz in order to obtain a reasonable number of samples in the entire frequency range (80 MHz to 1 GHz). Measurement results employing *peak* and *RMS* detectors are presented in Fig. 4. It is possible to observe that results were very similar to the ECL limits previously calculated and presented in Table 2.

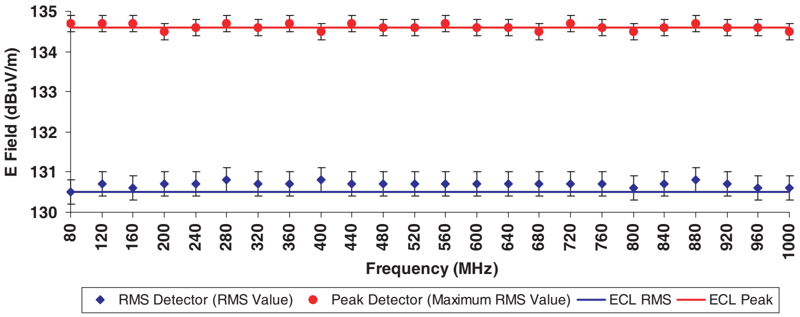

Figure 4. Measurement results for ECL (Compliance level 2). Variation bars are due to systematic measurement errors. Error variation is 0.2 dB for peak measurements and 0.3 dB for RMS measurements.

The use of RMS detector presented an average error of 0.2 dB and variations between 0.0 and 0.3 dB, whereas peak detector shows an average error of 0.0 dB and variations between −0.1 and 0.1 dB (observe that, according to its modulation features, peak detector acquires the maximum RMS values — and not the wave-peak value). Hence, this simple test can demonstrate an important outcome, since it confirms the expected results with a small amount of error. A further point to test confidence is related to the average results and system uncertainty (95% confidence interval, $k = 2$), once 130.7 ± 1.8 dBμV/m (RMS detector) or 134.6 ± 1.8 dBμV/m (peak detector) are in compliance with standards requirements and confirm ECL expectations.

5. DISCUSSION

Until now, most technical papers regarding environmental EMC management were based on a straightforward comparison of electromagnetic environmental measurements and immunity levels for electrical equipment. Since immunity levels 2 and 3 are the most commonly applied levels to equipment projected to operate under hostile electromagnetic environments, it is not difficult to find a number of papers using 3 and 10 V/m as a reference limit [1–9].

However, this work shows, through analytical and measurements results, that this approach represents a wrong or too conservative alternative to provide EMC management in critical areas. The overestimation amounts presented in the straightforward comparison basically depends on the type of detector employed in the environmental measurements. Table 2 has shown that this overestimation can be about 12% using RMS detector, and about 80% using peak detector (maximum RMS). Since peak detectors are commonly used to estimate worst-case conditions in environmental measurements, it represents an important source of concern.

In addition, an environmental compatibility level (ECL) definition is proposed in order to address an appropriate method to associate equipment immunity features and environmental conditions. The ECL definition represents the factual condition in which electrical and electronic equipment are exposed during immunity tests, and likewise, the real circumstances which they are able to operate without typical EMI problems. For instance ECL levels 2 and 3 provides respectively 5.4 and 18.0 V/m as a reference for environmental conditions. As long as environmental features remain under these limits, EMC should be successfully achieved promoting the proper operation of equipment.

As an example, it is possible to contrast the straightforward immunity level comparison and the ECL comparison method in order to evaluate their performance. Suppose that a given piece of equipment, in compliance with immunity Level 2 requirements, is operating within an environment whose critical frequency presents a 5 V/m wave-peak (e.g., 3.54 V/m *maximum RMS*). This environment must be evaluated according to short-term EMI noise (peak detector) in order to verify the operating condition of this equipment. If a straightforward comparison method is employed, the environment would be classified as non-compatible for equipment operation, since it exceeds the 3 V/m limit. Observe that this classification leads to an overly conservative analysis. On the other hand, if the ECL comparison method is applied, the environment would be classified as compatible with proper equipment operation, since it is below the 5.4 V/m limit (worst-case measurement). In fact, the 3.54 V/m *maximum RMS* is a compatible environment for Level 2 EMC certified equipment, because they were submitted to a worse condition during immunity tests. Therefore, it proves that the ECL comparison is a more reliable method to evaluate equipment immunity conditions.

The field of EMC measurements and wave propagation for environmental management is not completely developed and consolidated when compared to other areas of EMC engineering. Since the environmental condition is a modern concept regarding EMC definitions, it is possible to note that only some research groups present expertise in this area, whereas most part of EMC engineering still related to emission control and immunity developments (e.g., switching techniques, layout and grounding designs, filtering and shielding, interfaces and coupling mechanisms, electronic components technologies, and so forth), mainly due to the industrial and regulatory demands.

Additionally, it should also be noted that ECL limits proposed by this paper (or even the ordinary references of 3 and 10 V/m) were derived by IEC 61000-4-3 and, therefore, it did not consider safety issues. There is a tendency to think that it represents the maximum level in the environment concerning safety, but they do not. In fact it is expected that these levels could be exceed (about 5% of the time), but it represents an appropriate compromises between cost and immunity.

6. CONCLUSION

Analytical and measurement methods were developed in order to show the factual radiated immunity level in which electrical equipment are tested according to EMC standards [10]. This condition is defined as the environmental compatibility level (ECL) and should be used to verify environmental conditions during EMC management programs. Finally, this paper alerts to the importance of using ECL levels instead of simple immunity RMS levels during EMC management, as commonly observed in many papers in technical literature.

REFERENCES

1. Arnofsky, S., P. Doshi, K. Foster, D. Hanover, R. Mercado, D. Schleck, and M. Soltys, "Radiofrequency field surveys in hospitals," *Proc. of IEEE 21st Annual Northeast Bioeng. Conf.*, 129–131, May 1995.
2. Bassen, H., P. Ruggera, J. Casamento, and D. Witters, "Sources of radiofrequency interference for medical devices in the non clinical environment," *Proc. of the 16th Annual Int. Conf. of the IEEE EMBS*, Vol. 2, 896–897, Nov. 1994.
3. Boyd, S. M., W. S. Boivin, J. N. Coletta, C. D. Harris, and L. M. Neunaber, "Documenting radiated electromagnetic field strength in the hospital environment," *Journal of Clinical Eng.*, 124–132, Mar./Apr. 1999.
4. Davis, D., B. Segal, A. Cinquino, K. Hoege, R. Mastrocola, and T. Pavlasek, "Electromagnetic compatibility in hospital corridors," *Proc. of IEEE Int. Symp. on Electromag. Compatibility*, Vol. 1, 268–272, Aug. 1999.
5. Davis, D., B. Skulic, B. Segal, P. Vlach, and T. Pavlasek, "Hospital emergency room electromagnetic environment," *Proc. of 19th International. Conf. IEEE/EMBS*, Vol. 6, 2543–2546, Oct./Nov. 1997.

6. Phaiboon, S. and S. Somkuarnpanit, "Modeling and analysis the effect of radio-frequency fields in hospitals to the medical equipment," *Proceedings of TENCON*, Vol. 1, 92–95, Sep. 2000.
7. Schäfer, T., J. Maurer, J. Hagen, and W. Wiesbeck, "Experimental characterization of radio wave propagation in hospitals," *IEEE Trans. on Electromagnetic Compatibility*, Vol. 47, 304–311, May 2005.
8. Vlach, P., B. Segal, and T. Pavlasek, "The measures & predicted electromagnetic environment at urban hospitals," *Proc. of IEEE Int. Symposium on Electromagnetic Compatibility*, 4–7, 1995.
9. Young, C., A. Saoudy, and S. Budwill, "EMI levels at a 'patient care' location in a hospital," *Proc. of IEEE CCECE*, 625–628, 1997.
10. IEC 61000-4-3, *Electromagnetic Compatibility (EMC) — Part 4-3: Testing and Measurement Techniques-Radiated, Radio-frequency, Electromagnetic Field Immunity Test*, Edition 2.1, 107, Geneva, 2002.
11. ANSI Std. C63.2, *American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz — Specifications*, 25, New York, 1996.
12. ISO/BIPM, *Guide to the Expression of Uncertainty in Measurements*, 1st edition, Geneva, 1993.