Computing the Influence of Environmental Conditions in Electromagnetic Measurements Uncertainty

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Abstract—Testing and calibration laboratories should have a proven competency: they check devices and equipment quality, their generated field level and whether they fulfill product requirements or safety limits. That means expertise in applying standardized procedures, in controlling the possible measurement error sources, and in computing their associated uncertainty. This measurement uncertainty comes from different sources (site, equipment, operator, etc.), but there is one factor always present: the environmental conditions. In this paper, we examine the role that fluctuations in temperature and humidity conditions play in the measurement uncertainty of electromagnetic signals. A common issue in all tests is the attenuation of the propagated signal, so we first present the relation between signal attenuation, temperature, and humidity. Then, we quantify the uncertainty in the measured signal for some actual cases at certain conditions, starting by the attenuation effect and then considering other case specific deviations. We aimed to summarize the steps to compute the uncertainty associated to environmental conditions and to show that the relevance of each factor is case specific. Apparently low values could contribute to the uncertainty budget. Their relative impact has to be evaluated at least once, to decide if they should be minimized, corrected or discarded.

Index Terms—Electromagnetic measurements, humidity, temperature, uncertainty.

I. INTRODUCTION

CHARACTERIZATION of any equipment or device subject to radio emission requires precise measurements to determine their electromagnetic performance (household appliances, industrial and medical equipment, electronic devices, antennas, radars, etc.), which are often related to quality standards and/or must be compliant with defined specifications or safety limits [1]–[4]. This fact makes uncertainty computation a matter of concern, because the characterization of a parameter involves not only a measured magnitude, but also the uncertainty around it, which defines the interval where the true value is contained [5]. Factors contributing to the measurement uncertainty could come from the instrumentation, from the measurement site, and even from the device under test.

As far as possible, anechoic/reverberation chambers frequently host the tests of devices involving measurements of electromagnetic signals in order to have a controlled environment. Evaluating the chamber contribution to the uncertainty budget requires characterizing its performance [6]–[12]. When thinking about the issue, some characteristics pop into mind, as insulation from the external environment, ripple in the quiet zone, stray signals avoidance. It is well known, however, the attenuation effect that the water content of air, i.e. absolute humidity, has in the electromagnetic signals [13]. Thus, a full chamber characterization also involves analyzing the influence of the environmental conditions, i.e. temperature and humidity. On the other hand, some electromagnetic tests run outdoors, having this environmental analysis an added importance, as ambient conditions are out of operators’ control. In addition, a variation of temperature may also induce thermal effects in the measurement instrumentation, test devices, etc. that also lead to errors and deviations in the measured magnitude [14], [15]. A solution would be to characterize these uncertainties and to analyze their impact in the overall budget. Consequently, in some cases, temperature variations would have to be limited to keep measurement uncertainty below a certain value. Defining this limit is a requirement for the entities accredited under standards of quality, like ISO 17025 [1].

Along this paper, we show how to evaluate the uncertainty that fluctuating environmental conditions create in an electromagnetic signal received by an antenna. First, we present a summary of the fundamentals that relate the signal attenuation with the environmental conditions. Then, we illustrate their application with some actual scenarios. Finally, we draw some conclusions.

II. FORMULATION

Humidity, or in other words, the water vapor present in the air, produces an attenuation, A, in an electromagnetic signal travelling a distance d (in km) [13],

$$A = \gamma_w \cdot d$$  \hspace{1cm} (1)
being $\gamma_w$ the specific attenuation factor for water vapor in dB/km.

From sea level to an altitude of 10 km $\gamma_w$ is given by [13],

$$\gamma_w = 0.1820 \cdot f \cdot \sum S_i \cdot F_i$$  \hspace{1cm} (2)

where $f$ is the frequency in GHz, $S_i$ is the strength of the i-th water vapor line and $F_i$ is the water vapor line shape factor.

In the calculation of the line-shape factor, $F_i$, the elements involved are the frequency, the dry air pressure, the temperature, and the spectroscopic data for water vapor attenuation. The line strength, $S_i$, is a function of the water vapor partial pressure, the temperature, and the spectroscopic data for water vapor attenuation.

The water vapor partial pressure, $e$, may be obtained from the water vapor density, $\rho_{abs}$, and the temperature using the expression,

$$e = \frac{\rho_{abs} \cdot T}{216.7}$$ \hspace{1cm} (3)

being $T$ the temperature in K and $\rho_{abs}$ obtained by multiplying the relative humidity ($H_{rel}$, measured with a thermometer and expressed as a decimal) by the saturation water vapor content of air ($\rho_{sat}$) in g/m$^3$,

$$\rho_{abs} = H_{rel} \cdot \rho_{sat} / 100$$ \hspace{1cm} (4)

The saturation vapor density, in g/m$^3$, is obtained as,

$$\rho_{sat} = \frac{p_s}{R_v} \cdot T$$ \hspace{1cm} (5)

where $T$ is the ambient temperature in K, $R_v$ is the gas constant for water vapor (0.46152 J/K/g) and $p_s$ is the saturation vapor pressure in Pa at T Kelvin calculated using the Tetens’ equation [16],

$$p_s = 610.78 \cdot \exp(17.27 \cdot (T - 273.15) / (T - 35.85))$$ \hspace{1cm} (6)

III. UNCERTAINTY EVALUATION AT ACTUAL CASES

A. Measurements in an anechoic chamber

As first example, let us establish a scenario where tests perform in a chamber within a frequency range from 1 GHz to 50 GHz.

1) Uncertainty related to signal attenuation

When evaluating signal attenuation and for the sake of clarity and simplicity, instead of studying the contribution of environmental conditions to the measurement uncertainty in the whole frequency working range, we can define a worst-case scenario. This consists in conducting the study at the frequency with the highest attenuation due to water vapor. Attenuation was computed according [13] for the aforementioned range, obtaining the highest value at 22.66 GHz as shown in Fig. 1.

Once we know the frequency that represents the worst-error case, we could start applying the formulation in section II. First step was to define a range for the environmental conditions under which the measurements are going to be performed. Let them be a temperature of 20 ± 5 °C and a relative humidity of 45 ± 25%. When we talk about these variation ranges, we do not mean that such variations will take place during a single measurement, but we are considering that measurements can be repeated at different days or even seasons. The objective is to study the fluctuations in the measured values when we do not have humidity/temperature control, or when we do not measure them at each test, and we just have a humidity/temperature upper and lower limit.

For the given temperature range, the corresponding saturation vapor density was calculated by using (5) and (6). Fig. 2 shows the values obtained.

Then, we combined in pairs the saturated water vapor density and the relative humidity in the defined range (i.e. pairs of temperature and relative humidity), to evaluate all the possible combinations of environmental factors inside the chamber. With (2) we computed the actual water vapor density for each pair. With this value, and the corresponding temperature, the water vapor specific attenuation, $\gamma_w$, was calculated (see Fig. 3).

In the temperature and humidity ranges considered, the difference between the minimum and maximum values for

![Fig. 1. Specific attenuation due to water vapor for a pressure of 1013.25 hPa, a temperature of 15°C and a water vapor density of 7.5 g/m$^3$. Marker at the frequency with the highest attenuation.](image1)

![Fig. 2. Saturation vapor density.](image2)
water vapor specific attenuation is 0.32 dB/km. If the maximum measurement distance available in the chamber evaluated were 5 m, the maximum possible attenuation in the measurements inside the chamber, with the specified ambient conditions, would be 0.0019 dB, which can be translated into an uncertainty of ±0.001 dB around the mid-point. This small value is not significant in most of the anechoic chambers compared with other components of uncertainty, but represents an error source of the same magnitude as other contributions for testing labs working with low uncertainties. However, the contribution of this uncertainty factor is not relevant to the overall budget, even if it is as low as 0.2 dB [12], [17] – [20].

Out of this worst error frequency case, the attenuation decreases in several orders of magnitude, so it is clear that the influence is negligible even when compared with the less relevant components of uncertainty.

In addition, by having a temperature and humidity control system, or just by recording their fluctuations during each measurement test, we could correct the measurements with the values calculated for the attenuation, or reduce even more the associated uncertainty component.

The conclusion from this example is that the influence of environmental conditions should be evaluated at least once for the working frequency range and the required level of precision in our measurements. If such analysis shows that the uncertainty associated to the changes in the environmental conditions are not relevant, then the temperature controls required by some ISO standards [1] can be relaxed.

2) Uncertainties in the measurement instrumentation

Regarding the instrumentation commonly used for electromagnetic measurements in anechoic chambers, we can have the signal generator and the receiver as individual equipment or both integrated, as in a network analyzer. In both cases, manufacturers condition the validity of datasheet specifications to a certain operational temperature range, establishing it as a prerequisite for accurate measurements. One characteristic of interest, regarding accuracy in measurements, is the receiver linearity. A common value for this parameter in manufacturers’ datasheet is 0.1 dB [21]. As this is a less accurate estimation of the uncertainty, own specific measurements help to achieve a better characterization and minimization [18]. In this case, uncertainties of the order of 0.05 dB and even 0.01 dB can be obtained [18], [22]. In the case of taking the uncertainty due to receiver linearity directly from manufacturer specifications, the value due attenuation is negligible in view that the other component is 100 times larger. In the case that own measurements were performed, the influence of attenuation should be compared with other sources of uncertainty. At this point, we have to take into account that the environmental conditions inside the chamber may be different from those of the instrumentation.

3) Uncertainty in the device under test

Fluctuations of temperature may cause thermal expansion and contraction changes of the antennas used in the measurements. Let us take the example of an aperture antenna (one example is a horn one that is commonly used as reference/probe antenna) and the measurement of gain. The gain of this type of antenna is defined according to its size as [23]:

$$G = \frac{4\pi}{\lambda} A_{\text{eff}} = \frac{4\pi}{\lambda} \varepsilon_{\text{ap}} A_p$$

being, $A_{\text{eff}}$ the effective area, $\varepsilon_{\text{ap}}$ aperture efficiency and $A_p$ antenna physical area.

The gain variation that this type of antenna can suffer from ambient temperature fluctuations come from their associated dimensional variations. They depend on the constructing material and they are defined based on their thermal expansion coefficient ($\alpha_s$) [24]:

$$A = A_0 \cdot (1 + \alpha_s \cdot \Delta T)$$

where $A_0$ and $A$ are the starting and final area values respectively, $\alpha_s$ is the areal expansion coefficient and $\Delta T$ is the temperature variation.

The gain variation, in logarithmic units, due to the dimensional variations of the antenna is determined by:

$$\Delta G(\text{dB}) = 10 \log \left( \frac{4\pi}{\lambda^2} \varepsilon_{\text{ap}} A_p (1 + \alpha_s \cdot \Delta T) \right) - 10 \log \left( \frac{4\pi}{\lambda^2} \varepsilon_{\text{ap}} A_p \right)$$

$$= 10 \log \left( \frac{4\pi}{\lambda^2} \varepsilon_{\text{ap}} A_p (1 + \alpha_s \cdot \Delta T) \right) / \left( \frac{4\pi}{\lambda^2} \varepsilon_{\text{ap}} A_p \right)$$

$$= 10 \log (1 + \alpha_s \cdot \Delta T)$$

The maximum variation in temperature for this example is 10 °C. In addition to $\Delta T$, we need to know the antenna manufacturing material. Some common ones, and their thermal expansion coefficients [25], are summarized in table I. Last column of the table shows the fluctuation in the gain according (9).

In view of the magnitudes in table I, the considerations explained about the effect of signal attenuation are also applicable to the material thermal expansion.
 TABLE I

<table>
<thead>
<tr>
<th>Material</th>
<th>α₄ (°C⁻¹)</th>
<th>∆G (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>46.2-10⁻⁶</td>
<td>0.002</td>
</tr>
<tr>
<td>Brass</td>
<td>36-10⁻⁶</td>
<td>0.0016</td>
</tr>
<tr>
<td>Copper</td>
<td>33-10⁻⁶</td>
<td>0.0014</td>
</tr>
<tr>
<td>Zinc</td>
<td>60.4-10⁻⁶</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

The formulation for wire antennas is similar and relates the fluctuation in gain with the variation of the antenna length:

\[ \Delta G = 20 \log(1 + \alpha_r \Delta T) \]  \hspace{1cm}  \text{(10)}

being \( \alpha_r \) the linear expansion coefficient of the material.

For microstrip antennas, the temperature influences the value of the dielectric constant of the substrate, and can also produce contraction/expansion of the metallic part of the antenna.

The measured relationship between temperature and \( \varepsilon_r \) is given by [26]:

\[ \varepsilon_r \text{ (at } T \text{ °C)} = 0.00072 \cdot T + \varepsilon_r \text{ (at } 27 \text{ °C}) \]  \hspace{1cm}  \text{(11)}

In a rectangular patch, for the dominant TM010 mode, the resonant frequency of the microstrip antenna is given by:

\[ f_r = \frac{v_0}{2L \sqrt{\varepsilon_r}} \]  \hspace{1cm}  \text{(12)}

Thus, when the temperature increases, the value of the dielectric constant of the substrate material also does and the resonant frequency decreases.

For three of the substrates analyzed in [26] (FR4, Quartz, Polyamide), changes of 20 degrees in \( T \) lead to a maximum variation in gain of 0.01 dB. In the case of using Teflon, this also happens when temperature increases from 27 °C to 47 °C. For higher temperatures the difference is larger (from 0.03 to 0.04 dB), but such high temperatures are not expected in anechoic chambers. In our case, the maximum variation in temperature is 10 °C, so following the example in [26] we could expect a gain variation of around 0.005 dB. Despite these results are a bit worse than the ones obtained for aperture antennas, its contribution to the overall uncertainty budget is still negligible.

Moreover, in the case of probe or under test microstrip antennas that had been designed to compensate temperature effects [26] – [27], there is no need to consider the influence of the temperature. For wideband antennas on dielectric substrate, as Vivaldi (or Vivaldi-like flared notch, tapered slot antenna (TSA), endfire slotline antennas...), bowtie, spiral, UWB printed monopole antenna, etc., possible effects of environmental conditions fluctuations are expected to be less relevant, due to their wideband performance.

4) Uncertainties in the facility constructing materials

To achieve a space free of reflections, the walls of an anechoic chamber are covered with microwave absorbing materials. In the same manner as with the measurement instrumentation, manufactures provide the absorbers physical specifications defining the operational environmental conditions required. In any case, this is not a limiting factor as they can be made to stand up to extreme environmental conditions [28].

B. Measurements in an outdoor far-field antenna range

Some tests require high distances between the transmitter and the receiver, because of the frequency and/or the size of the device under test: outdoors facilities could range for hundreds of meters.

One example is the automated test-on-transmit antenna range of Ford Aerospace designed by the Howland Company [29]. The facility was designed to test satellite antennas of frequencies from 3.7 GHz to 14.5 GHz. To meet the far-field requirements for the diameters and frequencies of the antennas planned to test, the range length chosen was 7850 feet (2392.68 meters).

This case, due to the outdoor condition, presents a wider range of working values of temperature and humidity compared to the previous one. Variations of humidity between 15% and 75% and temperatures from 5 °C to 35 °C can occur considering different daytime hours, days or seasons.

1) Uncertainty related to signal attenuation

For the mentioned conditions, and by following the steps defined in the previous example, we compute the water vapor specific attenuation along the facility length at four different frequencies (maximum frequencies planned to be tested in the outdoor facility [29]): 4.1 GHz, 6.3 GHz, 11.7 GHz and 14.5 GHz.

Fig. 4 shows the values of the attenuation at 14.5 GHz (the largest ones) for the different pairs of temperature and humidity. Attenuation results follow the same trend in all the frequencies. Maximum values of attenuation at each one are summarized in table II.

![Fig. 4. Attenuation due to temperature and humidity at 14.5 GHz (case 2).](image-url)

**TABLE II**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Maximum attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>0.01</td>
</tr>
<tr>
<td>6.3</td>
<td>0.02</td>
</tr>
<tr>
<td>11.7</td>
<td>0.09</td>
</tr>
<tr>
<td>14.5</td>
<td>0.18</td>
</tr>
</tbody>
</table>
In [29] uncertainty of the test facility is estimated in 0.6 dB, so the values obtained for the attenuation due to environmental conditions are quite significant, for 11.7 GHz and 14.5 GHz, especially when the ambient humidity is high.

The uncertainty caused by the fluctuations in environmental conditions can be reduced registering their values during each measurement. Moreover, in the case we apply methods using reference antennas, as gain transfer method, if we transmit the reference and the test signals at the same time the effect is compensated.

2) Uncertainties in the measurement instrumentation

Environmental conditions in an outdoor range do not always comply with those defined in the operational range of the measurement instrumentation, so it should be housed in a closed enclosure site where the limits of fluctuation are lower. Thus, all the values provided in the previous example regarding this issue also apply to this case.

For the highest frequencies evaluated in this outdoor test case, values of uncertainty due to attenuation are comparable to those coming from receiver non-linearities given in the datasheet of measurement instrumentation.

3) Uncertainties in the device under test

Regarding the thermal expansion of antennas manufacturing materials, the values for this test case are in Table III ($\Delta T = 30 ^\circ C$). Values are between 13 times and 47 times smaller than the attenuation effect for the highest frequencies, thus, not very relevant. For the smallest frequencies, they are in a comparable range.

C. Measurements of human exposure to electromagnetic field strength from base stations

With this kind of measurements, what we would like to assess is if the electromagnetic field level measured at living areas, and created as a consequence of the power transmitted by the antennas from a base station, meets the established safety limits for human exposure. In this case, as in the previous one, it is not possible to control the environmental conditions as the measurements are performed outside, and their fluctuation over time is again higher than in indoor facilities.

Cellular networks operate on different frequency bands. 2G and 3G services, joined to LTE, involved frequencies in specific bands from 450MHz to 2600 MHz [30]. 5G auctions and trials are being conducted at considerably higher frequencies [31]: 3300-4200 MHz, 4400–5000 MHz, 24 – 33.4 GHz, 37–43.5 GHz, 47 GHz and there are even activities in the 64–86 GHz band.

The maximum exposure to the electromagnetic field generated by a base station is generally located in the area from a few tens to a few hundred meters away [32]. Some related legislation establishes the measurement to be carried in the area determined by the 100-meter radius from the base station antennas [33].

1) Uncertainty related to signal attenuation

With the mentioned frequency ranges and 100 meters as measurement distance, we did the same study as in the previous examples and under the same fluctuations of humidity and temperatures as in the outdoor antenna range (15% - 75% and 5°C - 35°C).

Some spot on the results are in Fig. 5. For the highest frequencies and values of temperature and humidity, the order of the attenuation is tenths of a dB. They are on the range of uncertainties coming from electromagnetic field probes as anisotropy or linearity [34], so they must be considered in the budget or corrected if recorded during the measurements.

2) Uncertainties in the measurement instrumentation

In addition to the attenuation, the temperature has another effect on the equipment used for exposure level measurements due to the deviation it causes on the field probe sensor [15]. For example, if the probe has a deviation of 0.02 dB/°C when the temperature varies from a reference of 23 degrees Celcius, in the range considered (5 °C - 35 °C) we have the deviations shown in Fig. 6.

3) Combined uncertainty

Combined uncertainty of both factors, signal attenuation and probe sensor deviation, considering a rectangular probability distribution and a coverage factor $k = 1.96$ (level of confidence of approximately 95 percent, recommended value for electromagnetic field strength measurements [34]) is drawn in Fig. 7.

When considering only the attenuation effect, the worst error cases were the ones with the highest values of humidity and temperature. If we also consider the deviation of the probe due to temperature, measuring at low temperatures introduces an important component of error. Thus, if we do not measure the temperature during the assessment of exposure level we have to add a component of uncertainty of 0.41 dB.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha_4$ (°C$^{-1}$)</th>
<th>$\Delta G$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>46.2·10^{-6}</td>
<td>0.006</td>
</tr>
<tr>
<td>Brass</td>
<td>36·10^{-6}</td>
<td>0.0047</td>
</tr>
<tr>
<td>Copper</td>
<td>33·10^{-6}</td>
<td>0.0043</td>
</tr>
<tr>
<td>Zinc</td>
<td>60.4·10^{-6}</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

Fig. 5. Attenuation due to temperature and humidity (case 3).
Fig. 6. Deviation of probe measurements related to temperature.

Fig. 7. Combined uncertainty for attenuation and sensor deviation.

IV. CONCLUSION

Fluctuations in temperature and humidity conditions throughout the measurement of an electromagnetic signal could add a component of uncertainty to the measured value.

In this paper, we summarize the formulation necessary to perform an assessment of the uncertainty associated to signal attenuation due to varying environmental conditions, and describe its application in a real case evaluation.

For this factor the magnitude of the evaluated uncertainty component depends on the range within the ambient conditions vary during the measurements and on the measurement distance. In addition, different tests require different levels of accuracy when reporting the measurement results. That means that the relevance of the ambient related uncertainty depends on the type of test to be performed, on the measurement site and on the control we can have over the variations of temperature and humidity. Thus, quantification of this uncertainty component should be performed for each measurement case to check its degree of influence in the uncertainty budget, compared with another sources of uncertainty.

From the data obtained in the examples analyzed along the paper, the contribution of humidity and temperature fluctuations on the attenuation could be considered negligible for conventional anechoic chambers. This could contribute to relax the control over environmental conditions given in some quality standards.

Some spots on other case specific deviations are also provided and compared with the influence of signal attenuation. They also help to illustrate the aforementioned idea: depending on the conditions of each measurement case, the effect of temperature and humidity on each variable of interest could be discarded or not. Thus, the study must be done at any case.

REFERENCES

Manuel García Sánchez (S’88–M’93) received the Ingeniero de Telecomunicación degree from Universidad de Santiago de Compostela, Santiago de Compostela, Spain, in 1990, and the Doctor Ingeniero de Telecomunicación (Ph.D.) degree from the Universidade de Vigo, Spain, in 1996. He is currently Professor at the Department of Signal Theory and Communications, Universidade de Vigo, Spain. He was head of the department from 2004 to 2010. His research interests include radio systems, indoor and outdoor radio channels, channel sounding and modeling for narrowband and wideband applications, interference detection and analysis, design of impairment mitigation techniques, and radio systems design.

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