Fast Simulation-Based tool for spherical antenna measurements: Uncertainty analysis

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***Abstract*- In this work, the study of the terms that contribute to de uncertainty in an antenna pattern measurement is proposed based on the use of simulation. First, both the measurement environment and the simulation tool that reproduces some of the characteristics existing in spherical measurements are presented. This tool's simulated radiation patterns have been validated by comparing with anechoic chamber measurements. Next, the terms of the uncertainty susceptible to be analyzed with the presented tool are introduced. The results are rapidly extracted from the simulations and then processed to obtain an estimation of the value of some of the uncertainty terms proposed by NIST.**

I. Introduction

The technical information generated by antenna test facilities is largely based on the results of measurements and the conclusions drawn from them. The utility of these results and the information provided by a laboratory is widely acknowledged to depend heavily on the quality of the accompanying uncertainty statements. This is especially true when methods involving a significant level of mathematical analysis, such as the near-field techniques, are used [1]. Therefore, it is important to recognize that measurement results are typically only approximations or estimates of the true value of the measured quantity, and that a complete understanding of the results requires a quantitative statement of their uncertainty. In fact, the uncertainty itself is a measure of the quality of the measurement, and enables comparisons between measurement results and other references (benchmarking), standards, or specifications. Ultimately, the uncertainty represents the range within which the error in the measurement can be expected to fall.

There are different ways of grouping the terms involved in uncertainty depending on the institution and the authors. Two of the most extended ones are the 21-term definition of the Antenna Centre of Excellence [2] and the 18-term one, accepted by the U.S National Institute of Standards and technology (NIST) [3]. The second one is the most widely used being the reference for the IEEE institution [4]. Therefore, this work will adopt the NIST standard following the IEEE recommendations.

Several works have been carried out in the literature around this topic. The possibility of obtaining some of the involved terms by using mathematical simulations is presented in [3], though it is focused on planar measurements. In [5], an 18-term uncertainty analysis was applied to a horn measurement at different frequencies but focusing on the effect in the side lobes and in a near field scenario.

In this work, a proposal of using a rapid simulation tool to obtain an estimation of the value of several of the uncertainty sources is presented. Given the high costs of equipment maintenance and the time needed to perform an antenna measurement in an anechoic chamber, it can be challenging to repeat the measurement in other to properly obtain some of the terms that will be presented. As a result, it could be very useful to have an approximation of the values even though the results might not have the same accuracy.

II. Simulation tool

A. *Spherical antenna measurement simulator*

When dealing with the experimental side of spherical measurements, the data is acquired over a spherical surface enclosing the antenna under test. There are different scanning procedures in a spherical scanning [1]. In this work an elevation over azimuth set-up is considered. This selection is justified by the measurement set-up currently available at the University of Oviedo facility. These facilities also offer the capability of near-field measurements and subsequent transformation to far-field through software. Additionally, there is provision for source reconstruction in order to perform diagnosis and near field to far field transformation [7] [8].

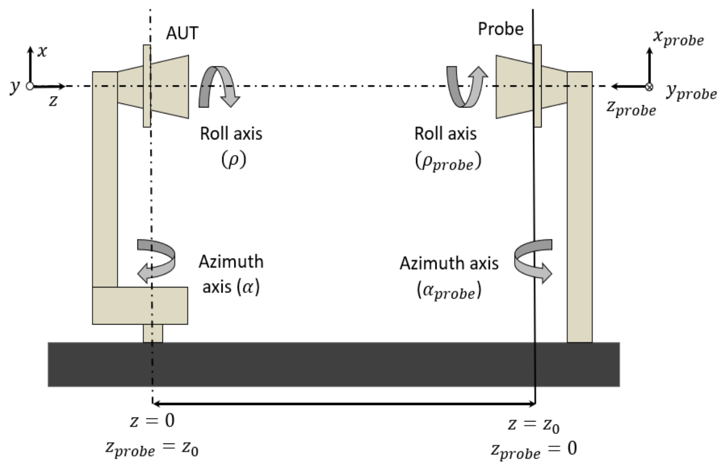

Fig. 1. Sketch of the elevation over azimuth set-up. The angle of rotation α_{probe} is only used for calculating misalignment errors but does not exist in the physical facilities. The probe is stationary and cannot be translated.

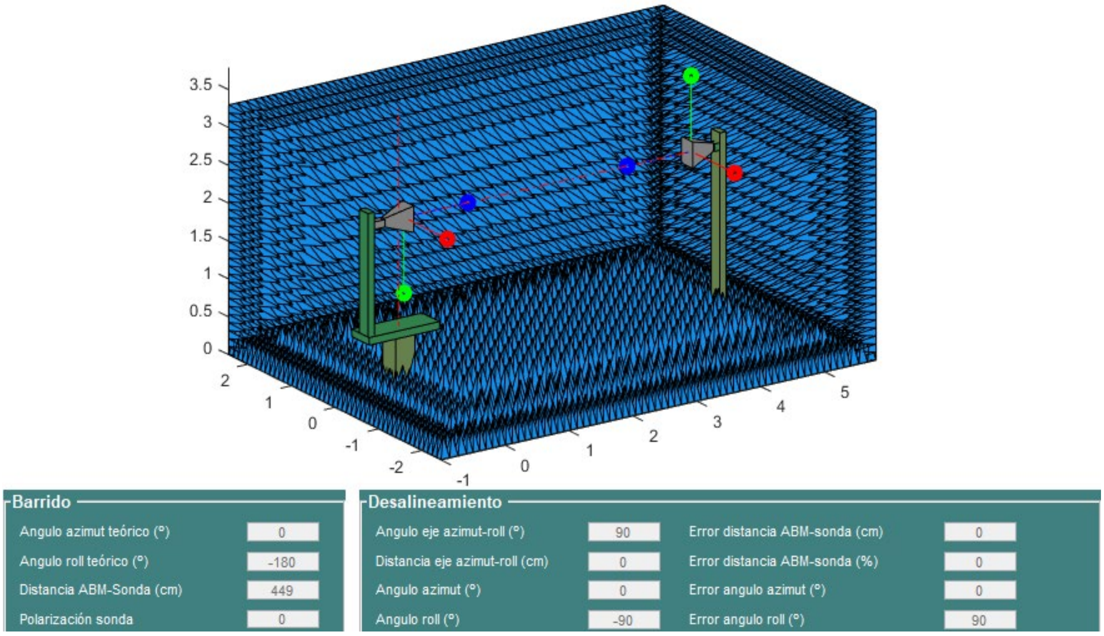

Fig. 2. Visual interface of the spherical range simulation tool.

This set-up, sketched in Fig. 1, has a quite complicated mechanical system for positioning so, for the geometric characterization of the measurement system in the spherical range, three reference systems have been considered: a local system associated with the measured antenna (AUT), another local system associated with the probe, and a global system common to both: the Cartesian coordinate system.

The relationship between the global system and the local system of the AUT depends on the azimuth (α) and roll (ρ) angles, taking the same point as the reference center for both systems.

The reference system of the probe is displaced by a distance z_0 with respect to the AUT. Additionally, alignment errors introduce a displacement and a rotation of the probe system, which must be characterized. The alignment error is given by the displacement with respect to the z-axis $(\Delta x, \Delta y)$, so the origin of coordinates of the probe reference system is the point $(\Delta x, \Delta y, z_0)$. On the other hand, the rotation error can be characterized by an azimuth rotation (α_{probe}) and a roll rotation (ρ_{probe}) of the probe.

For the calculation of the radiated field, the Equivalence Principle has been applied with an approximate model of the antenna that defines a distribution of equivalent currents only at the aperture. The size of the aperture and the current distribution over both the probe and AUT can be arbitrarily modified in order to match the desired measurement set-up.

B. *Experimental validation*

To validate the presented tool, an experimental measurement of a pyramidal horn antenna [6] with aperture dimensions of $0.35 \times 0.26\ m$ has been conducted at 2.5 GHz inside the anechoic chamber of University of Oviedo, and the results will be compared with those obtained from the simulation tool. Both the measurement and simulation environment consist of two identical pyramidal horn antennas with the same aperture size as the real one. Then an analytical calculation of the field over the aperture of the probe is performed.

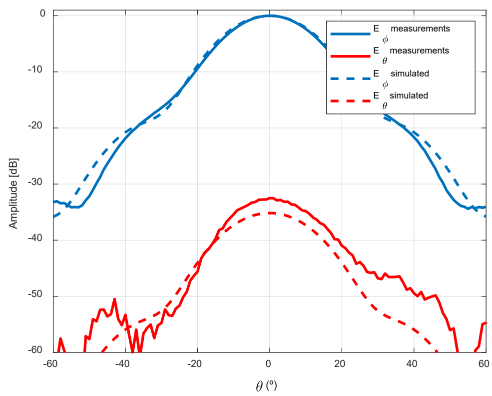

Fig. 3. Comparison between the measured and simulated electric fields in the ϕ =0º plane. The solid line represents the measured field in an anechoic chamber, while the dashed line represents the simulated field.

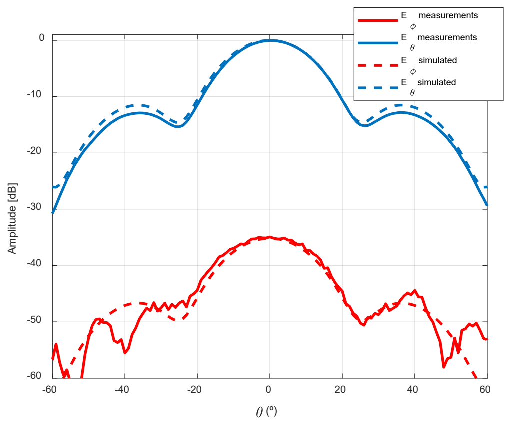

Fig. 4. Comparison between the measured and simulated electric fields in the $\phi = 90^o$ plane. The solid line represents the measured field in an anechoic chamber, while the dashed line represents the simulated field.

Fig. 2 shows the simulated set-up reproducing the real anechoic chamber. The measurements and the results extracted from simulation are compared in Fig. 3 and Fig. 4, showing tight agreement for both components in the principal cuts.

III. Uncertainty analysis

A. Review of uncertainty

In practical settings, numerous factors can impact the accuracy of a measurement, but by analyzing the measurement setup, it is possible to assess the overall uncertainty and establish upper and lower bounds within which the true value is anticipated to fall [1] .This uncertainty reflects the fact that a measured quantity is only one of many potential values that may exist around the physical real value and not this one itself. To estimate the overall uncertainty limits of a measurement and establish a corresponding confidence level, statistical analysis is typically used [9] .This approach requires knowledge of the magnitude and distribution of the various uncertainty components that contribute to the overall measurement uncertainty. Each of these components is represented by an estimated standard deviation, or standard uncertainty.

Following the IEEE recommendations in [4] it is possible to express the estimated uncertainty in two ways. The uncertainty can be given in terms of the change in the far-field parameter in dB or as fractional uncertainty.

In order to obtain these quantities a ratio (τ_{db}) between an equivalent stray signal (ESS) and the reference signal (S) is defined as:

$$\tau_{dB} = ESS_{dB} - S_{dB} \tag{1}$$

where both ESS and S are measured in voltage. In order to compare and combine terms it is useful to transform this ratio into an expression using logarithmic scale (dB). However, as presented in [10] using this kind of scales implies that an incremental value, for example, in terms of power, $+3dB$ represents an increment of +100%, does not imply the same magnitude change when used as a decrement, same example -3dB indicates a 50% reduction of the magnitude. This translates into the following expression for converting the previous ratio into a fractional uncertainty.

$$\Psi = \pm\left(10^{\frac{\tau_{db}}{20}} - 1\right) \tag{2}$$

where Ψ is the fractional uncertainty that can be now directly transformed into logarithmic form as:

$$\Psi_{\mathrm{dB}} = 20\log_{10}\Psi \tag{3}$$

B. Uncertainty terms

Not all the uncertainty terms can be analyzed though simulation as they are dependent on physical devices or unique properties of the materials used for each measurement set-up. The terms themselves will not be described in this paper as there are already treated in great detail in the literature [1] -[5]. Only practical considerations on how to obtain some of the terms will be briefly discussed next.

Probe relative pattern. The antenna's far-field pattern is initially determined by using a probe pattern that closely matches its actual behavior. This could be achieved by averaging several identical sets of measurements to reduce errors or just by assuming an ideal calculation of the probe as the reference pattern. Then, the far-field pattern is re-calculated using a probe pattern from a band immediately below the antenna's actual working band (in this work a frequency 1% below was selected). By comparing these two measurements, any uncertainty that arises due to disturbances in the probe's radiation pattern can be characterized. Typically, this error is believed to be less than the error introduced by using a lower frequency radiation pattern than the actual working frequency.

Probe polarization ratio. The simulation tool gives the possibility to obtain a pure linear polarization (the electric field vector of the wave remains in a fixed plane as the wave propagates), so by taking into account the axial ratio of the real antenna in the measurements, it is possible to reproduce the slightly elliptical polarization of the real horn and compare it with the purely linear one and obtain an estimation of the uncertainty. Other possibility is to follow the expressions presented in [1].

Gain standard. The gain of the AUT is usually calculated using either a direct gain technique or a comparison technique. In the direct gain technique, the probe acts as the gain standard, while in the comparison technique, another antenna, such as a standard gain horn, is used as the standard. Both analytical and computer simulations confirm that the uncertainty in the gain of the AUT caused by the gain standard is the same as the uncertainty in the gain of the standard [1] [4] . The uncertainty of the gain standard is usually obtained from calibration documents or estimates of uncertainty in the method used to determine the gain of the standard. In our case was extracted from the calibration documents.

Probe alignment. The mechanical systems available in the real measurement set-up have been calibrated and characterized so that the maximum error in spatial misalignments is 0.5 mm and 0.5º for angular errors. Using this information is possible to use a Monte-Carlo type method so that we can obtain an estimation for the uncertainty associated to probe misalignment. This value will include the contribution of all the mechanical uncertainty terms.

Data point spacing (aliasing). This term will be more relevant if near to far field transformation is used. In this case, the measurement is taken directly on the far field region. Thus, the obtained data points directly represent the radiation pattern. Therefore, any impact of the probe on the measurement results only affects when there are very few sampling points (not fulfilling Shannon criteria).

IV. Results

To apply the methods and procedures described in this study, a specific example was chosen to demonstrate the effectiveness of the suggested simulation tool. The analysis will be now particularized to the case of a standard gain antenna at 7 GHz with an aperture of 118.6×89.6 millimetres (Standard Gain Horn antenna, model 642 from Narda). The AUT is located at $z_0 = 4$ metres from the probe, ensuring that it at far field distance. This eliminated the need for near to far field transformations.

In order to illustrate the practical application of the proposed methodology, a comparison was made to obtain the NIST first term of the uncertainty. This comparison is presented in Fig. 5, which clearly shows the effectiveness of the simulation tool. The results of the analysis are presented in

Table 1, which shows the error budget of all 18 terms of the NIST analysis. This analysis provides some results of the effects of each error term on both the peak and side lobe levels of the measured pattern. This approach is more efficient and cost-effective compared to traditional measurement techniques and could be useful to apply as an estimator.

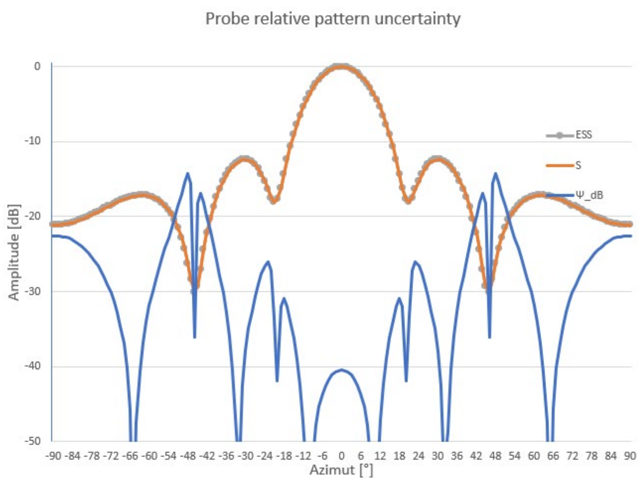

Fig. 5. Comparison between the reference signal (S) and the signal in a slightly lower frequency (ESS) along with the estimated uncertainty.

Source of uncertainty	Peak [dB]	SLL [dB]
1. Probe relative pattern	0,18	0,73
2. Probe polarization ratio	0,06	*n/a*
3. Gain standard	0,20	*n/a*
4. Probe alignment	0,42	1,64
5. Normalization constant or gain standard far-field peak	*n/a*	*n/a*
6. Impedance mismatch factor	*n/a*	*n/a*
7. AUT alignment	*[incl. 4]*	*[incl. 4]*
8. Data point spacing (aliasing)	0,00	*0,00*
9. Measurement area truncation	*n/a*	*n/a*
10. Probe transverse position errors (errors within scan surface)	*[incl. 4]*	*[incl. 4]*
11. Probe orthogonal position errors (errors orthogonal to scan surface)	*[incl. 4]*	*[incl. 4]*
12. Multiple reflections (probe/AUT)	*[meas.]*	*[meas.]*
13. Receiver amplitude nonlinearity	*[meas.]*	*[meas.]*
14. System amplitude and phase errors	*[meas.]*	*[meas.]*
15. Receiver dynamic range	*[meas.]*	*[meas.]*
16. Room scattering	*[meas.]*	*[meas.]*
17. Leakage and crosstalk	*[meas.]*	*[meas.]*
18. Miscellaneous random errors in amplitude/phase	*[meas.]*	*[meas.]*

Table 1 -Error budget for pattern measurements both for peak and SLL. *[meas.]*: needs to be measured. *[incl. 4]*: included in 4. Probe alignment.

V. Conclusions

This study aimed to propose an approach to calculating uncertainty terms in antenna measurements using simulation. The study emphasized the importance of quantitative uncertainty declarations in order to compare antenna measurements to other references, standards, or specifications. The NIST standard was adopted to ensure that the results were in line with widely used procedures. By utilizing a quick simulation tool to estimate uncertainty terms, this study demonstrates an affordable and efficient alternative to standard measurement techniques. The experimental validation of the proposed tool with a pyramidal horn antenna at 2.5 GHz in a spherical range in anechoic chamber has shown tight agreement with the simulation results, highlighting the potential of this approach for practical applications. Finally, an example of an error budget was given excluding the terms that need to be obtained through physical measurements.

Acknowledgements

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