Accurate Calibration of Truncated Spherical Near Field Systems with Different Ground Floors using the Substitution Technique

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***Abstract*—The calibration of the antenna measurements system is a fundamental step which directly influences the accuracy of any power-related quantity of the device under test. In some types of systems, the calibration can be more challenging than in others, and the selection of a proper calibration method is critical. In this paper, the calibration of the truncated spherical near-field ranges typically used for automotive tests is investigated, considering both absorbing and conductive floors. The analyses are carried out in a 12:1 scaled multi-probe system, allowing access to the "true", full-sphere calibration which is used as reference. It will be demonstrated that the substitution (or transfer) method is an excellent calibration technique for these types of systems, if applied considering the efficiency of the reference antenna.**

I. INTRODUCTION

System calibration is a fundamental step in any type of antenna measurements (e.g. Far Field / Near Field, passive / active) in order to test power-related quantities such as gain, efficiency, EIRP, and TRP. The so-called direct method [1-2] is a well-known calibration technique which requires knowledge of the system RF path (e.g. cables, amplifiers, switches, etc.), and the probe gain. While the latter can be characterized with dedicated radiated measurements, the former must be characterized with conducted measurements, which are often not practical because of the system size and/or accessibility to its components. To overcome these limitations, a reference antenna with known gain and/or efficiency can be measured in order to calibrate the system, implementing the so-called substitution (or transfer) method [1-2]. Even though it requires an additional measurement, this second method generally achieves higher accuracy because the uncertainty of the system calibration is basically reduced to the uncertainty related to the reference antenna.

In large spherical Near Field (NF) systems, like those used for automotive measurements, the scanning surface is usually truncated at, or close to the horizon, and terminated to a conducting or absorbing floor [3-4], as shown in Figure 1. The reflectivity of the ground floor combined with the truncation errors in the Near-Field-to-Far-Field (NF/FF) transformation may generate ripples in the measured pattern of the reference antenna during the system calibration. Such ripples in the pattern may compromise the accuracy of the calibration unless proper echo/truncation error mitigation techniques are used [5-6]. Alternatively, the substitution technique can be applied considering the known (spherical or hemispherical) efficiency of the reference antenna instead of its gain. The advantage is that the efficiency is directly related to the total power radiated by the antenna, which is relatively independent of the measurement setup.

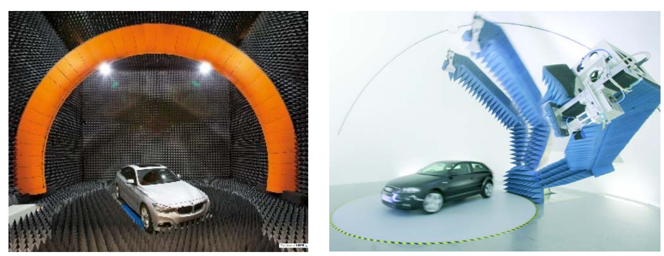

Figure 1. Examples of automotive spherical NF systems: multi-probe with absorbing floor (left); single probe with conductive floor (right).

Automotive systems like those shown in Figure 1 are both used to test the radiating performance of the vehicle installed antennas, and have different pros and cons. The absorber covered floor is intended to emulate a free-space environment, and is a key enabling factor to perform accurate measurements at low frequencies (down to 70 MHz). Moreover, the availability of the free-space response enables easy emulation of the car behaviors over realistic automotive environments with commercially available tools [7-8]. Such emulations are instead much more complex when a conductive ground is considered (see [9] for more details), and raw measurements over such type of floors are a good approximation of realistic grounds (such as asphalts) only in a limited number of situations. Moreover, measurements over conductive floors also suffer from a strong interaction between the ground-plane and the measurement system, thus the quality of the measurements is often compromised, especially at lower frequencies. On the other hand, the main advantages of these type of system are the ease of the accommodation of the vehicle under test, and the simplification of the NF/FF transformation [4], enabling amelioration of the truncation errors.

In this study, scaled automotive spherical NF setups with both absorbing and conductive ground floors will be taken into account, to prove experimentally that the efficiency calibration method can be applied to accurately calibrate truncated ranges, regardless of the ground floor material.

II. Substitution Calibration Methods

The substitution (or transfer) calibration method is based on the measurement of a reference antenna with known efficiency or gain values [1-2]. From the measurement of the reference antenna, a Calibration (or Correction) Factor (CF) is computed as the difference (in dB) between the reference and the raw measured value. Such calibration factor is then applied to the measured data of the test antenna. The simplest and most widespread way to implement the substitution technique is to consider the boresight gain of the reference antenna (gain substitution method). In such case, the CF is obtained as the difference between the reference (G_{Ref}) and the measured raw (G_{Meas}) boresight gain of the calibration antenna as shown in equation (1):

$$CF_{Gain} = G_{Ref} - G_{Meas} \tag{1}$$

The main advantage of using the gain substitution method is that the reference boresight gain of the calibration antenna (G_{Ref}) can in many cases be obtained accurately, and at a reduced cost, by simply performing single-point far-field measurements in certified facilities. However, G_{Meas} might be affected by errors introduced by the measurement environments, such as reflections (in case of FF and NF ranges) and truncation of the scanning area (in case of NF ranges).

To overcome such issues, it is convenient to calibrate the systems considering the efficiency (η) of the reference antennas (efficiency substitution method) as depicted in equation (2):

$$CF_{\eta} = \eta_{Ref} - \eta_{Meas} \tag{2}$$

The antenna efficiency is defined as the ratio between the gain and the directivity or, equivalently, as the ratio between the total radiated power and the power delivered to the antenna. η_{Ref} can thus be obtained by measuring the reference antenna in full spherical ranges where the total radiated power is computed by the integration of the measured pattern. Alternatively, the Wheeler-cap test setup can be implemented [10], but is well-known to have practical limitations in case of wideband and/or electrically large antennas.

The main advantage of using the efficiency substitution method is that possible errors generated by ripples on the pattern (i.e. caused by reflections) are averaged, and thus reduced by the integration of the measured raw pattern. Another advantage derived from the pattern integration is that the alignment of the calibration antenna is not critical (in principle any antenna orientation is fine). The total efficiency calibration method is accurate only if in the system to be calibrated, at least two fundamental conditions are met: 1) the total radiated power over the entire sphere can be measured accurately, and 2) the total radiated power is not modified by the measurement set-up (e.g. the antenna matching should not be affected by the environment).

Unfortunately, in a truncated spherical NF system with the ground floor covered by absorbers (see Figure 1, left), the power radiated on the backward hemisphere is lost and thus the total radiated power cannot be measured. In such cases, it is convenient to consider the Upper-Hemispherical efficiency (η^{UH}) defined as the ratio between the power radiated on the forward/upper hemisphere (i.e. from the Zenith to the Horizon of the sphere) and the delivered power. Such type of systems can be calibrated with equation (3):

$$CF_{\eta^{UH}} = \eta^{UH}_{Ref} - \eta^{UH}_{Meas} \tag{3}$$

where η^{UH}_{Ref} can be obtained considering the subset of the measured reference pattern with $|\theta| \leq 90°$ and η^{UH}_{Meas} is measured directly in the range to be calibrated. It should be noted in this case, the unwanted effect caused by the truncation of the scanning range (ripples in the pattern) are averaged out in the pattern integration. It should be further noted in this specific case, the Wheeler-cap method cannot be applied, since the upper-hemisphere power cannot be separated from the lower hemisphere.

When measurements are performed over metallic grounds like the system shown in Figure 1 (right), the floor is assumed to be a Perfect Electric Conductor (PEC). In such cases the power radiated in the backward hemisphere is fully reflected by the (lossless) ground, hence the power on the upper hemisphere is the same of the total radiated power that the antenna would radiate in free-space over the full sphere. The calibration factor in this case can be obtained as the difference between the reference (full) efficiency (η_{Ref}) of the calibration antenna and the measured hemispherical efficiency (η^{UH}_{Meas}) as shown in equation (4):

$$CF_{\eta^{PEC}} = \eta_{Ref} - \eta^{UH}_{Meas} \tag{4}$$

It is highlighted that this latter calibration method can be used only if the ground floor does not modify the matching of the calibration antenna. This is a reasonable assumption for antennas with low back-radiation, such as horns and monopoles/monocones mounted on their own ground plane.

III. Test Cases Description

Experimental verifications of the calibration methods described in the previous section have been carried out considering the scaled-model technique [11], in order to emulate some automotive test scenarios with different ground floors, such as those shown in Figure 1. The scaled-model technique is based on the basic concept that the EM performance of a generic antenna system depends on its dimensions in terms of wavelengths (electrical size).Therefore, if the physical dimensions are multiplied by a factor N and the frequency is divided by the same factor N, the electromagnetic behavior is perfectly maintained for fully metallic objects. The advantage of using the scaled-model technique in this situation, is the possibility to have access to full-spherical free-space data that can be used as a baseline, in order to assess the calibration accuracy of different scenarios.

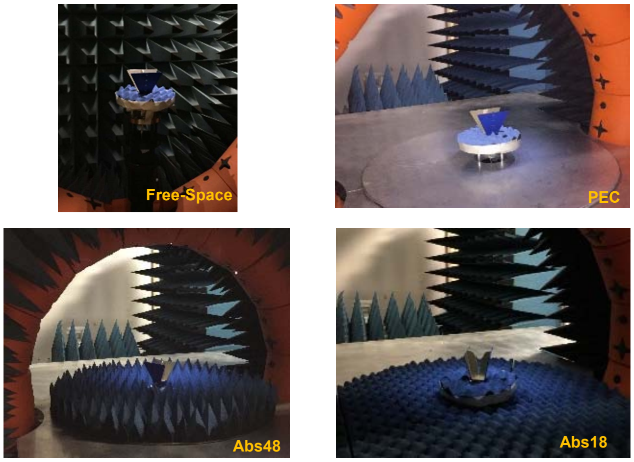

Figure 2. SH2000 antenna during calibration in the different scenarios: free-space, 48-inch (Abs48) and 18-inch (Abs18) scaled absorbers and metallic floor (PEC).

Two reference antennas have been measured in the StarLab-18GHz (SL18GHz) multi-probe system, where different floors have been implemented (see Figure 2.). The SL18GHz is comprised of two interleaved probe arrays capable of measurements in the 0.4-6 GHz and the 6-18 GHz frequency ranges, respectively. The measurement radius of the system is 45 cm. The considered calibration antennas are two wideband dual-ridge horns designed by MVG: the SH800 (not shown for briefness), and the SH2000 [12]. The SH800 has been measured in the 1008 – 6000 MHz range with the low-frequency (LF) probe array, while the SH2000 was measured in the 6-18 GHz range with the high-frequency (HF) probe array.

Considering $N = 12$ as scaling factor, the performed measurements are equivalent to the measurements of 12 times larger antennas, measured respectively between 84-500 MHz and 500-1500 MHz, performed in a system with a 5.4m radius.

The calibration antennas have first been measured in free-space conditions over the full-sphere, as shown in the top-left part of Figure 2. To emulate the two typical automotive system ground conditions (see Figure 1), a metallic ground has been introduced inside the system. As depicted in the top-right part of Figure 2, the metallic ground floor is composed by a 75 cm-diameter turntable which rotates with the antenna, and by a fixed metallic part which extends outside the system. The metallic plane is placed 11 cm below the center of the system. This displacement allows for measurements down to approximately 10° below the horizon (corresponding to approx. 100° of elevation scanning). PEC-based measurements have been carried-out with this setup (see Figure 2, top-right).

Two types of absorbing materials have been placed on the turntable in order to emulate absorbing-floor-based systems, like the one shown in Figure 1 (left):

- 4-inch pyramidal absorbers (Figure 2 bottom-left)
- 1.5-inch convoluted absorbers (Figure 2 bottom-right)

With the considered scaling factor ($N = 12$), the 4-inch absorbers are equivalent to 48-inch (Abs48) height full-size absorbers, which are typically used down to 70-80 MHz. Similarly, the 1.5-inch absorbers are equivalent to 18-inch (Abs18) height full-size absorbers and are typically used starting from 400-500 MHz. Despite this, the scaled 18-inch absorbers have been considered in the whole tested frequency range (84-1500 MHz), since they could be an attractive solution for measurements at lower frequencies (80-400 MHz), due to their cost advantage and ease of measurement configuration when compared to the 48-inch absorbers.

TABLE I. NOMINAL REFLECTIVITY AT NORMAL INCIDENCE OF THE CONSIDERED ABSORBERS [13].

Measured Frequency	Scaled (1:12) Frequency	4-inch absorbers (Abs48)	1.5-inch absorbers (Abs18)
1 GHz	83MHz	n/a	n/a
3 GHz	250 MHz	-30 dB	n/a
6 GHz	500 MHz	-35 dB	-20 dB
10 GHz	833 MHz	-40 dB	-30 dB
15 GHz	1250 MHz	-45 dB	-35 dB
18 GHz	1500 MHz	-50 dB	-36 dB

The nominal reflectivity at normal incidence of the considered absorbers is reported in Table 1. It should be noted that with this type of approach only the physical dimensions of the absorbers are properly scaled. The conductivity (losses) of the absorbers cannot be scaled (as it should be, according to the scale-model method [11]). In this specific case, the reflectivity of the considered scaled absorbers is 5 to 10 dB higher than the one of the full-size absorbers [13] meaning that a "worst-case" scenario is considered with respect to the real one. Nevertheless, this has been assumed to be a reasonable approximation, providing a representative emulation of the real scenario.

IV. RESULTS

The spherical NF acquisitions of the two calibration antennas have been performed in the four scenarios (see Figure 2.) and the FF has been computed with NF/FF transformations [14]. Free-space and absorber-based measurements have been processed with the conventional Spherical Wave Expansion (SWE) NF/FF approach [14], simply considering zero-padding in the truncated areas. The PEC-based measurements have instead been processed enforcing the PEC boundary condition during the NF/FF [4]. To do that the Translated-SWE (TSWE) technique [15] has been used to translate the reference system along z-axis in order to have the PEC interface at $z = 0$ (it is recalled that the conductive floor is 11 cm below the arch center).

A comparison of the measured E-plane pattern cut at 500 MHz (SH2000 at 6 GHz) in the four scenarios is shown in Figure 3. As can be seen, the pattern is not normalized and its level is thus associated to the losses of the system (i.e. the unknown object of this study). The black-dashed trace is the pattern measured in free-space over the full-sphere (the baseline). The green and orange traces are the patterns measured respectively for the scaled 18-inch and 48-inch absorbers over 100° in elevation. The effect of the truncation is evident at angles larger than 90°, where the pattern is strongly attenuated. Moreover, some ripples caused by the abrupt discontinuity introduced by the zero-padding [6] are present in the proximity of the truncation angle of 100°. The blue trace is the pattern measured over the PEC. Such pattern is of course defined only in the forward hemisphere and is affected by strong ripples caused by the interaction with the conductive floor.

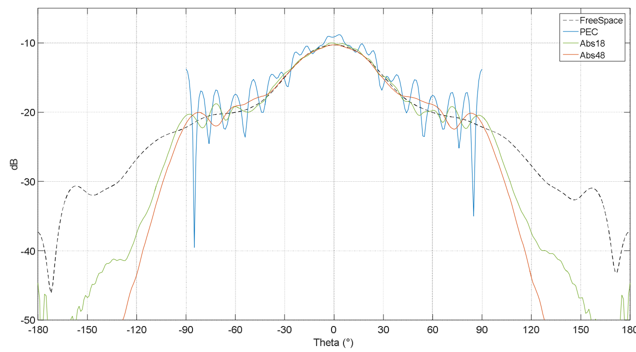

Figure 3. Measured E-plane pattern cut of the SH2000 calibration antenna at 6 GHz (representative of 500 MHz) in free-space and different floor scenarios.

A first calibration analysis has been carried out considering only the free-space measurements. Such data have been used to perform a (boresight) gain calibration using equation (1), and an efficiency calibration using equation (2), and to identify the differences between them. The considered reference gain and efficiency values of the calibration antennas are typical measured data, TYMEDA™ [16]. In Figure 4, the absolute value of the difference between efficiency and gain calibration coefficients ($|CF_{\eta} - CF_{Gain}|$) is reported for the both LF and HF probe arrays of the system. As expected, these deltas are relatively low (0.4 dB at max), and within the uncertainty of the system, meaning that in a free-space full-spherical scenario the two calibration methods could be considered equivalent. The observed differences are probably associated to the not-optimal anechoic environment where the measurements have been performed, and the not-perfectly RF transparent supporting structure used to hold the antenna, which might interact with the measurement. For the reasons pointed out in section II, the efficiency calibration method should be less sensitive to these errors, hence, in the following analysis CF_{η} is used as the reference calibration factor.

Gain calibrations have been performed considering the measurements taken over the three different ground floors. To affect that, the boresight gain of the measured antennas has been considered in equation (1). The results in terms of absolute deviation of the obtained CF with respect to the reference CF are reported in Figure 5, for both the LF and HF probe arrays. Green and orange traces are the deviations obtained respectively with 18-inch and 48-inch absorber floors. The errors are higher at lower frequencies (> 1 dB at some points), where the reflectivity of the absorbers and the truncation errors are expected to be worse [13]. Such error sources influence the accuracy of the measured pattern, and thus the calibration which is done considering a single point of the pattern (the boresight). The accuracy of the calibration is of course even worse, if the gain substitution method is applied to the PEC-based measurements (blue traces), which are inherently associated with high reflectivity. In such cases in fact, due to the high reflectivity levels introduced by the conductive floor (see for example pattern distortion in Figure 3), up to ~3.5 dB of calibration errors are obtained.

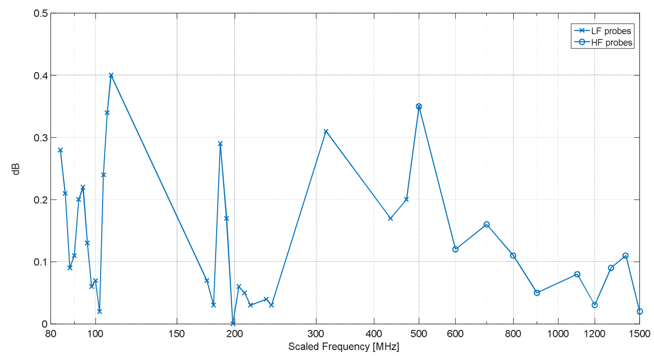

Figure 4. Difference (absolute value) between the CF obtained with efficiency and gain calibration.

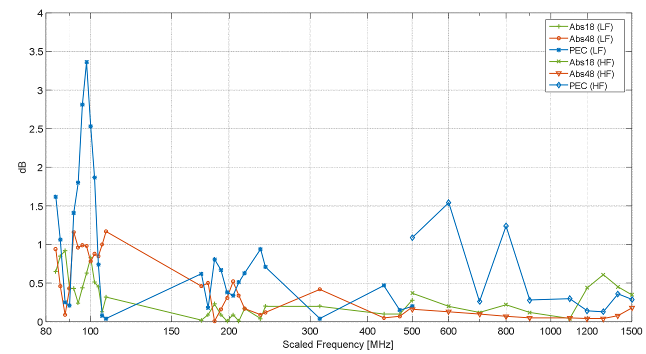

Figure 5. Differences (absolute value) between the reference CF and the CF obtained with gain calibration of the different ground scenarios.

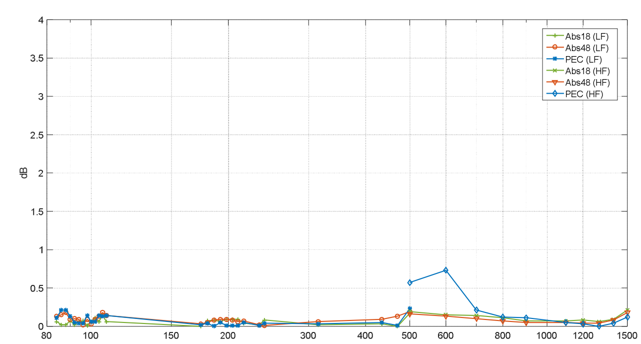

Figure 6. Differences (absolute value) between the reference CF and the CF obtained with efficiency calibration of the different ground scenarios.

The same comparison shown in Figure 5 is repeated in Figure 6, considering the different efficiency calibrations instead of gain calibrations. Specifically, equation (3) has been considered to calibrate the absorber-floor-based measurements with the upper-hemisphere efficiency. As can be seen, the deviations with respect to the free-space reference calibration is below 0.2 dB across the whole considered frequency range, for both the 18-inch and 48-inch absorbers (see green and orange traces respectively). Equation (4) has instead been used to calibrate the PEC-based acquisitions. Even in this case the deviation with respect to the reference calibration are within 0.2 dB at almost all the frequencies, except for a couple of frequency points where slightly higher deviations (0.6-0.7 dB) have been noted (and are currently under investigation).

These latter results demonstrate that the efficiency substitution method can be used to accurately calibrate full-spherical, absorber- and PEC-based spherical NF systems.

V. Conclusions

In this paper, the calibration of spherical NF truncated systems with absorbing and conductive (PEC) floors have been investigated. Such systems are widely used in the automotive industries in order to test the radiation performance of the antennas installed on the vehicle. The analysis has been carried out in the 84-1500 MHz frequency range considering a 1:12 scaled multi-probe system, where two types of absorbing floors and a conductive ground have been considered. The used scaled absorbers emulate the 48-inch and 18-inch height full-size absorbers. While the formers are normally used down to 70-80 MHz, the latter are typically used starting from 400-500 MHz.

The substitution technique has been considered to calibrate the different scenarios. This technique is based on the measurement of a reference antenna with known gain or efficiency, which is then used to derive the losses of the systems (including the RF path and the probe gain). The considered calibration antennas are two wideband, dual-ridge horns (the SH800 and SH2000).

The substitution technique has been applied in each ground scenario, considering both gain and efficiency calibration. As expected, the efficiency calibration produced much more accurate results when compared to the gain calibration. This is due to the fact that the efficiency is an integral quantity, hence errors on the pattern caused by the reflectivity and/or truncation of the areas are averaged, and thus reduced. The gain calibration is instead more sensitive to these types of errors, because only a single point in the pattern (the boresight) is considered.

It has been demonstrated that absorber-based systems can be calibrated accurately by considering the upper-hemisphere efficiency of the calibration antennas. Excellent calibration results have been obtained with both the considered absorber types, across the entire bandwidth. Even though additional tests would be needed, the 18-inch absorbers could thus be an attractive solution for measurements at lower frequencies (80-400 MHz), because they are less expensive and easier to handle than the 48-inch absorbers.

Finally, it has also been shown that PEC-based systems can be accurately calibrated with the efficiency substitution method. In such cases, the reference values of the calibration antenna to be considered is the full efficiency, as in the system the power radiated on the lower hemisphere is reflected in the upper hemisphere.

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