# Experimental Validation of the Translated-SWE Technique Applied to Automotive Measurements over PEC-Floor at Arbitrary Height

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***Abstract*—Automotive antenna testing performed on large, truncated spherical near-field systems, able to host the entire vehicle under test, are an industry standard. The truncated scanner is often terminated to a conductive floor where the vehicle is staged for testing. Despite the strong interaction with the reflective floor, such systems are often employed because of the ease of car accommodation and measurement setup. Moreover, if the conductive floor lies on the horizon plane, truncation errors can be easily reduced in the near-field to far-field transformation by simply mirroring the measured field (image theory).**

**Due to mechanical constraints, or extension of the operational mode of some systems (e.g. absorber-based systems), sometimes the floor position doesn't correspond to the horizon plane, and advanced techniques are needed to extrapolate the truncated area. The Translated-SWE technique, already presented in the past, is proposed for such purpose and will be validated experimentally considering scaled automotive measurements.**

***Index Terms*— automotive, vehicle test, spherical near field, PEC, reflectivity, truncation, ground floor, spherical wave expansion, NF/FF transformation.**

## I. INTRODUCTION

Modern antennas for automotive applications are strongly integrated with the vehicle, hence testing of the entire car system are required [1]. Due to the size of the vehicles, outdoor direct Far Field (FF) measurements are sometimes performed. However, due to the weather conditions and electromagnetic pollution, they may lack in measurement accuracy and repeatability. Measurements performed in shielded controlled environments, like anechoic chambers, are thus usually the preferred solutions [1]. To contain size and cost of the chamber, tests are in most cases performed using Near Field (NF) systems where the FF performances are evaluated in post-processing with NF/FF transformation tools [2-3]. The most widespread kind of NF system for automotive applications has a spherical geometry (Spherical NF, SNF) truncated at, or close to, the horizon [1, 4-6]. As shown in Fig. 1, different implementations of such systems are available, and they mainly differ in the type of scanning mechanism (electronical scanning with multi-probe arches [1] or mechanical scanning with single-probe gantry-arms [4-5]) and the floor type employed. The floor can be either covered by absorbing materials emulating a free-space environment, or a conductive (metallic) surface.

A typical implementation of automotive multiprobe system with absorbing floor provided by MVG is shown in Fig. 1 (left) [1]. These kinds of systems allow fast and accurate measurements down to 70 MHz. The absorbing material is placed on a metallic floor, and the floor is positioned below the arch center (1m to 2m depending on the system, close to the top of the measured vehicle) in order to extend the validity area of the measured pattern below the horizon. The location of the floor below the horizon allows to reduce the truncation errors in the NF/FF transformation [5]. Furthermore, the car behavior over realistic grounds (e.g. asphalt/soil) could be emulated by using proper software tools [7-8]. The main drawback of such type of system is the additional setup time needed to place the absorber around the vehicle.

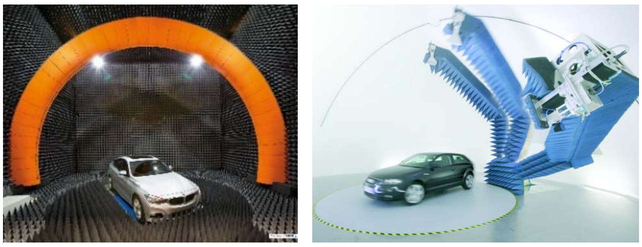

Fig. 1. Examples of automotive spherical NF systems: multi-probe system with absorbing floor (left); single-probe gantry-arm system with conductive floor (right).

A typical implementation of a conductive floor system with single-probe gantry arm provided by MVG is shown in Fig. 1 (right). The conductive floor of such systems is normally positioned on the horizon plane (i.e. coincident with the center of the measurement sphere) and assumed to be a Perfect Electric Conductor (PEC). By applying the image theory [9-10], the field measured on the upper hemisphere is properly mirrored into the lower hemisphere, simplifying the NF/FF transformation process and mitigating the truncation errors [4, 6, 10]. Another advantage of this type of systems is the ease of accommodation of the vehicle, which can be simply parked in the center of the system. On the other hand, the measurement accuracy of such systems is often degraded by the strong interaction with the fully reflective floor [11], and only for a few cases is the PEC condition a good approximation of realistic automotive grounds.

The above-mentioned advantages of the PEC-based systems, together with some possible already-defined test procedures, make measurements over conductive floors the preferred solution and/or a desirable option. Absorber-based systems like the one shown in Fig. 1 (left), could be also used as a PEC-based system by simply removing the absorbers. In such cases, the enforcement of the PEC boundary condition in the NF/FF transformation is complicated by the fact that the PEC interface is below the center of the measurement sphere. To accurately perform the field transformation in such situations, the Translated Spherical Wave Expansion (TSWE) technique [12-13] can be exploited. The TSWE allows to arbitrarily define the origin of the coordinate system in spherical NF measurements. As demonstrated in previous publications, this allows to conduct the measurement with a reduced number of samples in the case of offset antennas. By moving the coordinate system on the PEC interface, TSWE can also be used to properly enforce the PEC boundary condition. This feature of TSWE can also be exploited in any PEC-based system where the floor is not on the horizon plane, because of mechanical constraints or similar. This approach is similar to the one also described in [5].

In this paper the use of TSWE as a NF/FF transformation tool for over-PEC measurement at arbitrarily height is experimentally demonstrated for the first time. Scaled measurements of a car model have been conducted in the StarLab multiprobe system, considering a metallic floor below the horizon. The pattern results have been compared to the reference ones obtained by measuring the same device with the metallic floor placed on the horizon plane.

## II. NF/FF TRANFORMATION OVER PEC-FLOORS AT ARBITRARY HEIGHT

The spherical NF/FF transformation is conventionally performed utilizing the Spherical Wave Expansion (SWE) technique. As widely described in [3], the acquired NF is first projected on a set of orthogonal spherical basis functions, computing the Spherical Wave Coefficients (SWC). The SWC represent the radiated field everywhere in space outside the Antenna/Device Under Test (AUT/DUT) minimum sphere (i.e. smallest sphere centered in the origin of the coordinate system fully enclosing the DUT). The FF is thus computed from the SWC.

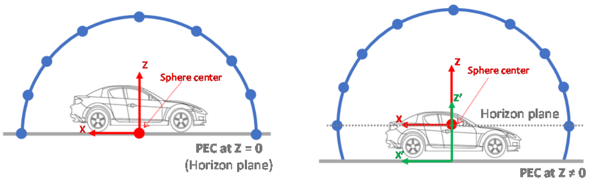

Fig. 2. Schematic of a PEC-based systems: floor on the horizon plane (left); floor below the horizon plane (right).

The SWE requires the SNF to be defined on the whole sphere. Hence, when dealing with truncated spherical acquisitions, to reduce the truncation error the missing portion of the scanning area must be extrapolated. Different extrapolation techniques can be applied [6].

When the acquisition is performed over a good conductor, it can be assumed to be an infinite PEC as shown in Fig. 2. According to the image theory [9], the radiation in the upper hemisphere of any device radiating above a PEC is equivalent to the one of the same device in free space, superimposed with its image with respect to the PEC plane. Truncated SNF measurements over a PEC can thus be effectively extrapolated by mirroring the measured field with respect to the metallic floor interface. If the conductive floor lies on the horizon plane (i.e. plane intersecting the center of the measurement sphere) as shown in Fig. 2 (left), the field can be simply described as reported below

$$E_\theta^{Full}(\theta,\varphi) = E_\theta\,(\theta,\varphi) + E_\theta\,(180^\circ - \theta,\varphi)$$
$$E_\varphi^{Full}(\theta,\varphi) = E_\varphi\,(\theta,\varphi) - E_\varphi\,(180^\circ - \theta,\varphi)$$

where $(E_\theta^{Full}, E_\varphi^{Full})$ are the full (measured plus extrapolated) field components and $(E_\theta, E_\varphi)$ are the measured field components with $\theta = [0{,}90^\circ\,)$ and $\varphi = [0{,}360^\circ)$. As described in [10] it could be applied directly on SWC by simply redoubling the amplitude some of them and setting the others to zero. This property, known as PEC boundary condition, can be exploited as an alternative to the before-mentioned extrapolation.

The PEC boundary condition cannot be applied as easily as described above if the conductive floor is not on the horizon plane as shown in Fig. 2 (right). To overcome this limitation, the Translated-SWE (TSWE) technique can be applied. The TSWE has been introduced in previous publications [12-13], demonstrating that it can be effectively used as a NF/FF transformation tool for down-sampled SNF measurements of offset-mounted antennas. The TSWE in fact allows the definition of a virtual reference system that can be chosen arbitrarily. For example, if the antenna to be measured is mounted offset with respect to the center of the measurement sphere, it is convenient to define the reference system on the antenna itself, generating a smaller minimum sphere and thus relaxing the sampling requirements (down-sampling) [12-13].

In the present case, TSWE can be exploited to define a new reference system with the origin located on the conductive floor interface (see primed green coordinate system in Fig. 2-right). This allows us to take advantage of the symmetry with respect to $z' = 0$, and thus apply the image theory. Once the new reference system is properly defined with TSWE, the SWC are directly computed with the PEC boundary condition property mentioned above.

As explained in [13], the main drawback of the TSWE technique is its higher computational cost with respect to the conventional SWE. The usual equally-spaced sampling on the measurement sphere is not anymore equally-spaced in the translated reference system. This implies that the Fast Fourier Transform (FFT) cannot be applied as typically done with the

SWE for the $\theta$- and $\varphi$-dependency [3]. Nevertheless, if the translation is along the $z$-axis, as in the present case, the FFT is still applicable for the $\varphi$-dependency, maintaining the relatively low complexity.

## III. EXPERIMENT DESCRIPTION

The scaled-model technique [14] has been considered in order to validate the proposed application of TSWE. 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 divided by a factor $N$ and the frequency is multiplied by the same factor $N$, the electromagnetic behaviour is maintained for fully-metallic objects.

A 1:12 scaled-car model (Morris Minor 1000 of 1965) fed by patch antennas has been measured in the StarLab-18GHz (SL18GHz) multi-probe system [15] in two different configurations. The SL18GHz is comprised of two interleaved probe arrays capable of performing measurements in the frequency ranges from 0.4-6 GHz and 6-18 GHz, respectively. The measurement radius of the system is 0.45 m. As can be seen in Fig. 3, three similar wideband patch antennas have been installed in three different positions on the car model: close to the windshield, on the rear part of the roof, and on the hood of the scaled vehicle, respectively. In each measurement, only one patch is fed while the other two are terminated with a matched load. The chosen test frequency is 6 GHz. Therefore, with the considered $N = 12$ scaling factor, the performed measurements are equivalent to the ones of a full-size vehicle (real dimensions are L x W x H = 3.76 x 1.55 x 1.52 m) measured in a system with a 5.4 m radius at 500 MHz.

Fig. 3. Scaled vehicle with patch antennas in three different positions.

To emulate a PEC-based system a metallic ground has been introduced in the system. Such 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. Conductive contacts have been included in the junction between the two metallic parts in order to ensure the electrical continuity. Measurements have been performed with the metallic floor at two different heights:

- On the horizon plane ($z = 0$ cm) as shown Fig. 4 (left). This emulates a conventional PEC-based scenario like the one shown in Fig. 1 (right) and schematized in Fig. 2 (left). In the following we will refer to this set-up as “at-horizon” measurements;

- 11 cm below the horizon plane ($z = -11$ cm) as shown Fig. 4 (right). This correspond to a position of 1.32 m in real dimensions and emulate a multi-probe-like scenario like the one shown Fig. 1 (left - without the absorbers) and schematized in Fig. 2 (right). In the following we will refer to this set-up as “below-horizon” measurement.

The first one has been used as baseline/reference while the second one as a test case to validate TSWE.

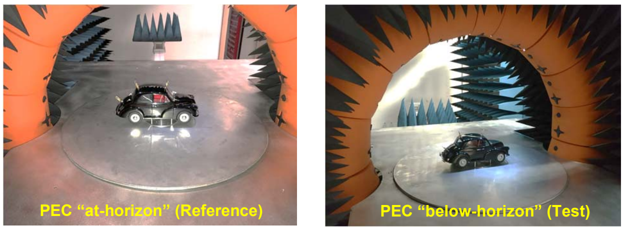

Fig. 4. Scaled vehicle measured over conductive floor at different heights: floor at Z=0 (left); floor at Z=-11 cm (right).

## IV. RESULTS

Results in terms of directivity patterns of the considered scaled vehicle measured over the metallic floor at two different heights are reported in this section. Results are presented for the three antennas located on the vehicle: hood, rear part of the roof, and close to the windshield.

The “at-horizon” acquisitions have been transformed to FF considering conventional PEC-based mirroring technique previously described, and the standard SWE-based NF/FF transformation [3]. These results are considered as the reference. The “below-horizon” measurements have instead been transformed to the FF with the proposed TSWE technique, hence moving the reference system on the metallic floor and imposing the PEC boundary condition directly on the SWC. For comparison, the same measurements have also been processed with the conventional PEC-based mirroring technique and NF/FF technique.

Elevation directivity-pattern comparisons along the vehicle’s longest dimension at 500 MHz for the “hood” antenna (scaled from 6000 MHz) is reported in Fig. 5. The blue trace is the reference pattern. The black-dashed and orange traces are the patterns obtained from the “below-horizon” measurements, processed respectively with the conventional PEC-based mirroring / SWE, and with the proposed TSWE. As expected, the deviations of the “below-horizon” measurements processed with the standard approach from the reference are quite large because the PEC condition is not applied at the correct position. It should be noted that such deviations are more pronounced at angles corresponding to the PEC interface (close to $\theta = 90°$). Instead, when TSWE is applied (accounting for the correct location of the metallic floor), a correct behaviour is obtained, and the agreement with the reference is very good over the entire pattern.

A similar comparison is reported in Fig. 6 for the azimuthal cut at 5° above the horizon ($\theta = 85°$). Even along this cut, the performance of the TSWE technique applied to the "below-horizon" measurement is very good.

Elevation and azimuths pattern comparisons along the same two cuts previously shown for the "hood" antenna are now reported in Fig. 7 and Fig. 8 for the "rear roof" antenna. Similarly, figures 9 and 10 report the same comparison for the "windshield" antenna. Also for these antenna configurations, significant improvements can be observed when the "below-horizon" measurements are processed with TSWE.

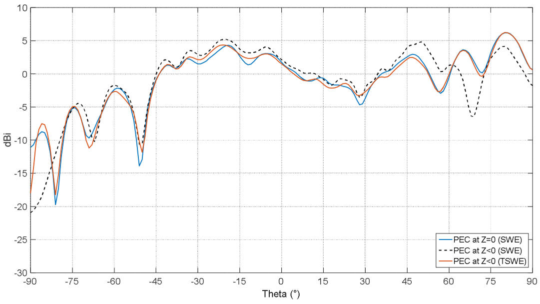

Fig. 5. Elevation directivity pattern comparison at 500 MHz (scaled frequency) for the "hood" antenna.

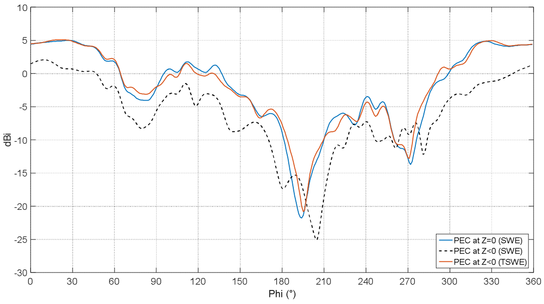

Fig. 6. Azimuth directivity pattern comparison at 500 MHz (scaled frequency) for the "hood" antenna.

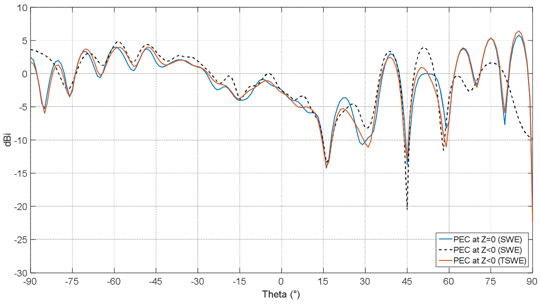

Fig. 7. Elevation directivity pattern comparison at 500 MHz (scaled frequency) for the "rear roof" antenna.

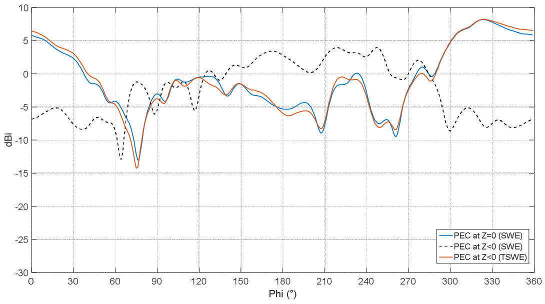

Fig. 8. Azimuth directivity pattern comparison at 500 MHz (scaled frequency) for the "rear roof" antenna.

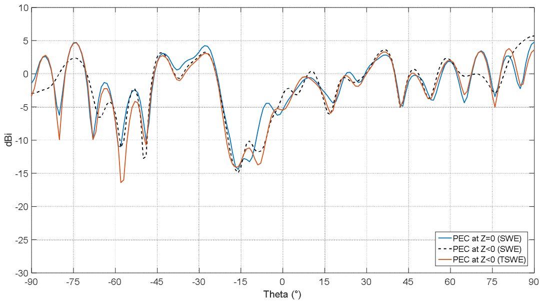

Fig. 9. Elevation directivity pattern comparison at 500 MHz (scaled frequency) for the "windshield" antenna.

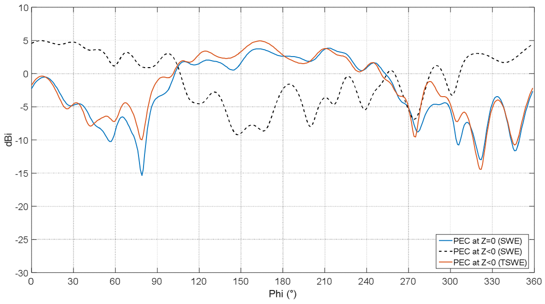

Fig. 10. Azimuth directivity pattern comparison at 500 MHz (scaled frequency) for the "windshield" antenna.

To quantify the improvements obtained, we can compute the Equivalent Noise Level (ENL), defined as,

$$ENL = 20\log_{10}\left( RMSE \left| \frac{E(\theta,\varphi) - \tilde{E}(\theta,\varphi)}{E(\theta,\varphi)_{MAX}} \right| \right)$$

In such expression, $E(\theta,\varphi)$ is the reference and $\tilde{E}(\theta,\varphi)$ is the pattern under analysis. The ENL has been evaluated on the entire upper hemisphere (i.e. $|\theta| \leq 90°$), considering the total field normalized in directivity. The obtained ENL for the three antenna configurations measured in "below-horizon" PEC scenario is reported in Table I for the Standard-SWE (conventional extrapolation and conventional NF/FF) and

TSWE processing. The improvements obtained by applying the TSWE technique are on the order of 10 dB for all the investigated antenna positions.

TABLE I. ENL ON THE WHOLE HEMISPHERICAL PATTERNS.

| **Antenna Position** | **Standard-SWE [dB]** | **Translated-SWE [dB]** |
|---|---|---|
| Hood | -23.0 | -32.5 |
| Rear Roof | -22.8 | -34.6 |
| Windshield | -22.8 | -29.2 |

## V. CONCLUSIONS

The Translated Spherical Wave Expansion (TSWE) technique has been proposed as an effective NF/FF transformation tool for automotive spherical NF measurements performed over conductive floors placed at an arbitrary height.

Measurements over conductive floors are often involved in automotive testing because of the ease of vehicle accommodation and measurement set-up. In such systems, the NF/FF transformation is simplified when the floor coincides with the horizon plane (plane intersecting the center of the measurement sphere), because the PEC boundary condition can be easily enforced by mirroring the measured field. Instead, it becomes more complex when the floor is below or above the horizon plane. The latter scenarios are typical when mechanical constraints are present in the test set-up and/or when a system designed for other type of measurements is used as a conductive floor system (e.g. multiprobe system with absorbing-floors). In such situations the TSWE technique can be used because it facilitates defining a new reference system on the conductive floor plane, thereby enabling the proper enforcement of the PEC boundary condition.

The use of the TSWE technique for such type of measurements has been successfully validated considering scaled automotive measurements performed in the StarLab multiprobe system, where a conductive floor has been implemented for these tests. The validation has been carried out considering a 1:12 vehicle model fed by antennas in three different positions.

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