Comparative Investigation of Spatial Filtering Techniques for Ground Plane Removal in PEC-Based Automotive Measurements

F. Saccardi, F. Mioc, L. J. Foged
Microwave Vision Italy SRL
Via dei Castelli Romani 59, 00071, Pomezia, Italy
francesco.saccardi@mvg-world.com

J. Estrada, P. O. Iversen
MVG, Inc
450 Franklin Gateway Suite 100 30067 Marietta, GA, US
john.estrada@mvg-us.com

M. Edgerton
GM Proving Grounds
3300 GM Rd, 48380, Milford, MI, US

J.A. Graham
GM Technical Fellow Antenna Development and Performance (Retired)

***Abstract*—Radiating performances of vehicle-installed antennas are typically performed in large spherical near-field systems able to accommodate the entire car. Due to the size and weight of the vehicle to be tested, such spherical systems are often nearly hemispherical, and the floor is conductive or covered with absorbers. The main advantage of the first is the ease of the accommodation of the vehicle under test. Conversely, the latter is more time consuming in the setup of the measurements because the absorbers need to be moved in order to be placed around the vehicle. On the other hand, the absorber-covered floors emulate a free-space environment which is a key enabling factor in performing accurate measurements at low frequencies (down to 70 MHz). Moreover, the availability of the free-space response allows easy emulation of the cars' behaviors over realistic automotive environments (e.g. roads, urban areas etc.) with commercially available tools. Such emulations are instead much more challenging when a conductive floor is considered. Furthermore, the raw measurements over conductive floors are a good approximation of realistic grounds (such as asphalts) only in a limited number of situations. For these reasons, when PEC-based automotive measurements are performed, it is often required to retrieve the free-space response, or equivalently, to remove the effect of the conductive ground.**

In this paper two spatial-filtering techniques (the spherical modal filtering and the equivalent currents) will be experimentally analyzed and compared to verify their effectiveness in removing the effect of the conductive floor. For this purpose, a scaled automotive PEC-based measurement setup has been implemented considering a small spherical multi-probe system and a 1:12 scaled car model. The two techniques will be analyzed considering two different heights of the scaled car model with respect to the conductive floor.

I. Introduction

Modern automotive antenna measurements are performed in shielded anechoic chambers using spherical near-field systems [1-2]. Due to the physical size of the vehicles to be tested, and to contain the cost of the chamber, the scanning surface is usually truncated at, or close to the horizon, and terminated at the floor where the vehicle is placed, as shown in Figure 1. The floor is often covered with absorbing materials, which emulate the free-space condition [3]. Alternatively, a conductive ground plane, which is assumed to be a Perfect Electric Conductor (PEC), is also considered [4-5]. The main advantage of this second solution is the ease of vehicle installation, where the vehicle is driven directly to the test position. Conversely, when absorbing materials are considered, time is required to place them around the vehicle, and it may be necessary to raise the vehicle to avoid absorber shadowing. Another advantage of the PEC-based solution is related to the truncation errors, which in most cases, are fully removed by mirroring the upper hemisphere measured data onto the lower hemisphere (image theory application) [4-7]. On the other hand, the response of the vehicle over a PEC is not a good approximation of certain type of realistic grounds, such as dry asphalts and soils, which are strongly dielectric. Instead, the free-space response can be considered a decent approximation of a realistic ground, e.g. dry asphalt. Moreover, if a more accurate evaluation of the final environment is needed, the free-space response can be used as an input to commercially available post-processing tools designed for this purpose [8].

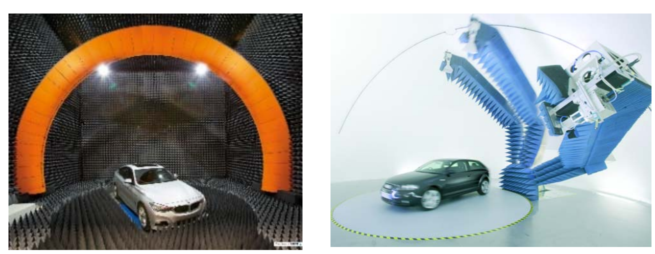

Figure 1. Examples of automotive spherical NF systems: multi-probe with absorbing floor (left); single probe with conductive floor (right).

The free-space response retrieval from measurements over a PEC is thus a desirable feature, but also a challenging task because of the strong coupling between the ground and the vehicle under test.

In this paper, two spatial filtering techniques (the spherical modal filtering [9] and the equivalent currents [9-11]) will be applied to scaled automotive PEC-based measurements to experimentally evaluate and compare their effectiveness in the cancellation of the conductive floor. In the analysis, two different separations between the vehicle and the floor will be considered in order to verify how the distance from the ground can improve the rejection of the effect of the PEC floor.

II. Spatial Filtering Techniques

The spatial filtering techniques considered in this study to remove the metallic ground are the spherical modal filtering and Equivalent Currents (EQC) technique. A brief description of these two techniques is reported below.

A. Spherical modal filtering

First, the spherical modal filtering [9] implemented in the commercially available MV-Echo tool [12] is considered. This tool takes advantage of the spatial filtering properties of the Spherical Wave Expansion (SWE) [2] of the measured field. The scattered field components, being highly oscillating, are attributed to higher order modes that can be eliminated by filtering the modal spectrum. The minimum number of spherical modes required to fully represent the antenna depends on the physical size of the minimum sphere or cylinder fully enclosing the antenna. With MV-Echo, the AUT minimum sphere/cylinder can be minimized with translation/rotation operations, resulting in a more effective low-pass spatial filtering. The workflow considered to retrieve the free-space response from measurements over the PEC is schematized in Figure 2. The input scenario is the Far Field (FF) of the vehicle above an infinite PEC ground. Due to the image theory [6-7], the input scenario is equivalent to the original vehicle plus its image (mirrored replica of the car with respect to the horizontal axis). The image could be seen as an echo source. By moving the reference system to the center of the car, the image is translated and therefore represented by higher order modes of the modal spectrum. These modes can be removed with a low-pass filtering, applied in the form of a cylinder (as done in this analysis) or a sphere. It should be noted that due to the coupling with the PEC, the image cannot be fully removed, resulting in a residual error. Such error can be reduced by increasing the electrical distance between the PEC-floor and the vehicle. This procedure is thus expected to work better at higher frequencies.

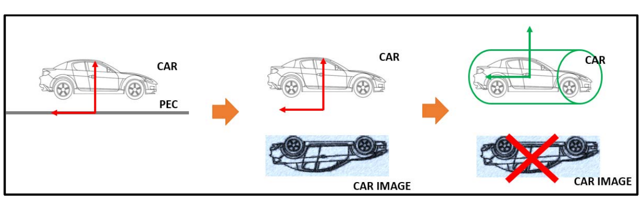

Figure 2. Modal filtering principle.

B. Equivalent Currents

Starting from the measured NF or FF data, the EQC technique, implemented in the commercially available Insight software [13] enables the computation of the equivalent electric and magnetic currents on an arbitrarily-shaped reconstruction surface fully enclosing the test object. The availability of the EQC allows for several type of advanced processing, including antenna diagnostics [10], links with computational EM software [14], and spatial filtering [9, 11]. The latter capability has been exploited in this study. The workflow of the procedure is very similar to the one shown Figure 2 in case of MV-Echo. For the first step, the measured FF over PEC is represented as the superposition of the vehicle and its image. The EQC are then reconstructed on an equivalent box including the vehicle and its image as shown in Figure 3 (left). The currents associated to the image are then "switched-off" as shown in Figure 3 (right) and the FF is recomputed from the filtered currents.

The advantage of the use of the EQC technique is that a finer reconstruction geometry can be defined, allowing for a more effective spatial filtering when compared to the modal filtering technique (where the spatial filter can be defined only with spheres and cylinders). This could allow for a better rejection of the image, even when the vehicle is located directly on the floor.

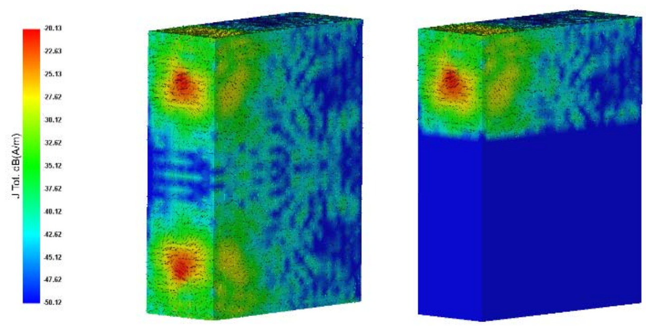

Figure 3. EQC of the vehicle and its image (left); Filtering of the vehicle image (right).

III. Test Cases Description

A scaled automotive measurement setup has been implemented in order to compare the effectiveness of the previously described spatial-filtering techniques in the removal of the effect of the metallic floor. The scaled-model method [15] has been considered in order to emulate realistic automotive test scenarios. Such method 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 method in this situation is the possibility to have access to full-spherical free-space data that can be used as a baseline/reference, in order to assess the accuracy of the considered spatial-filtering techniques.

A 1:12 scaled-car model (Morris Minor 1000 of 1965) fed by a patch antenna has been measured in the StarLab-18GHz

(SL18GHz) multi-probe system in different configurations (see Figure 4 and Figure 5). 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. The measurement radius of the system is 45 cm. As can be seen in Figures 4 and 5, three similar wideband patch antennas have been installed in three different positions: 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 on a matched load. Measurements have been performed in the frequency band 1.008 -18 GHz. 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 5.4m radius in the 84-1500 MHz band.

In this analysis, only the measurements relevant to the patch installed in the hood position have been considered. It should be noted that the chosen antenna location represents a worst-case scenario, since it is closer and thus more coupled with the conductive floor.

Beforehand, a free-space, (quasi) full-spherical acquisition has been performed, as shown in Figure 4, and considered as a reference.

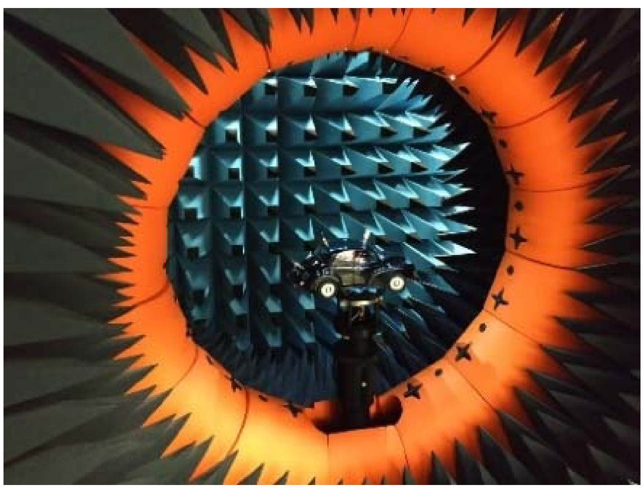

Figure 4. Free-space measurement of the scaled vechicle used as reference.

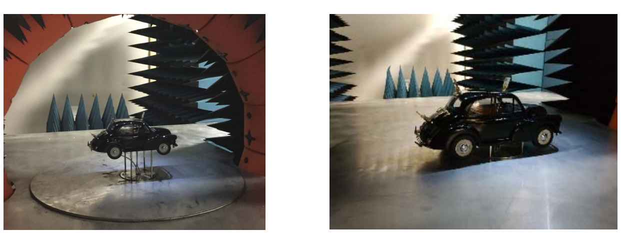

Figure 5. Scaled PEC-based measurement scenarios: car raised (left); car on the floor (right).

To emulate a PEC-based automotive system scenario, a metallic floor has been introduced inside the system. As depicted in Figure 5, such floor is composed by a 75cm-diameter metallic turntable which rotates with the vehicle, and by a fixed metallic part that extends outside the system. Conductive contacts have been included in the junction between the two metallic parts in order to ensure the electrical continuity. In the setup, the floor is placed 11 cm below the center of the scanner (corresponding to a position of 1.32 m in real dimensions) to emulate real automotive systems where the top of the car is located close to the center of the spherical scan. Such displacement allows measurements from approximately 10° below the horizon (corresponding to approx. 100° of elevation scanning). As shown in Figure 5, the scaled vehicle has been measured in two different configurations: 7.5 cm (corresponding to 0.9 m) raised from the floor ("raised" configuration), and at the ground level ("floor" configuration), as shown on the left and right side of Figure 5, respectively. As explained in the previous section, in the raised configuration the electrical separation between the vehicle and the ground is increased, and thus the coupling is reduced, allowing for a better rejection of the metallic floor with both techniques. Both filtering techniques have been analyzed in both configurations, "raised" and "floor".

IV. RESULTS

The spherical NF acquisitions of the scaled vehicle in the different configurations have been processed with the NF/FF transformations [1-2] in order to get the FF. In particular, the free-space measurements have been processed with the conventional Spherical Wave Expansion (SWE) NF/FF approach [2]. Instead, the PEC-based measurements have been processed enforcing the PEC boundary condition during the NF/FF [4-6]. To do that, the Translated-SWE (TSWE) technique [16] has been used to translate the reference system along the 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). Finally, the obtained FF has been normalized in gain, taking advantage of the system gain calibration performed with the substitution method [1], as described in detail in [17].

The gain-normalized FF pattern coming from the PEC-based measurements have been provided as input to the two spatial filtering tools that are the object of this study, in order to remove the effect of the metallic floor. MV-Echo has been applied at all the measured frequencies, considering as a spatial filter the smallest cylinder including the vehicle, as shown in Figure 2. Insight has instead been applied to three frequencies, namely 84, 240 and 500 MHz (scaled frequencies), considering a box enclosing both the vehicle and its image as reconstruction geometry. An example of the reconstructed EQC at 500 MHz in the case of the raised configuration is shown in Figure 3 (left). As shown in Figure 3 (right), the currents associated to the image have then "switched-off."

A. Vehicle raised from the floor

Considering the vehicle raised from the metallic floor, the gain pattern comparisons at 84, 240 and 500 MHz are reported in Figure 6 from top to bottom, respectively. The plots in the first column show the comparison in the φ=0° elevation cut (the one along the car longest dimension), while the plots in the second column show the comparison along the θ=85° azimuth cut (the one being 5° above the horizon). The black-dashed traces are the reference free-space pattern while the orange-dashed traces are the "raw" pattern measured over the PEC (patterns over PEC in the lower hemisphere are just a mirrored replica of the upper hemisphere resulting from the application of the PEC boundary condition). As expected, the comparisons of these two patterns highlight large differences between the two different measurements scenarios. The blue traces are the retrieved free-space (FS) pattern obtained with MV-Echo. The agreement with the reference is good at 240 and 500 MHz approximately up to |θ|=90° (the forward hemisphere). At 84 MHz, the electric separation between the vehicle and the metallic floor is too small (approx. 0.25 wavelengths), and it does not allow for a good rejection of the vehicle image. The green traces are the retrieved FS pattern obtained with Insight. Even in this case, the rejection of the image at 84 MHz is poor, because of the reduced separation distance. At 240 and 500 MHz, the agreement with the reference pattern on the upper hemisphere is good and similar to the one obtained with MV-Echo. On the lower hemisphere instead, much better results are obtained with Insight.

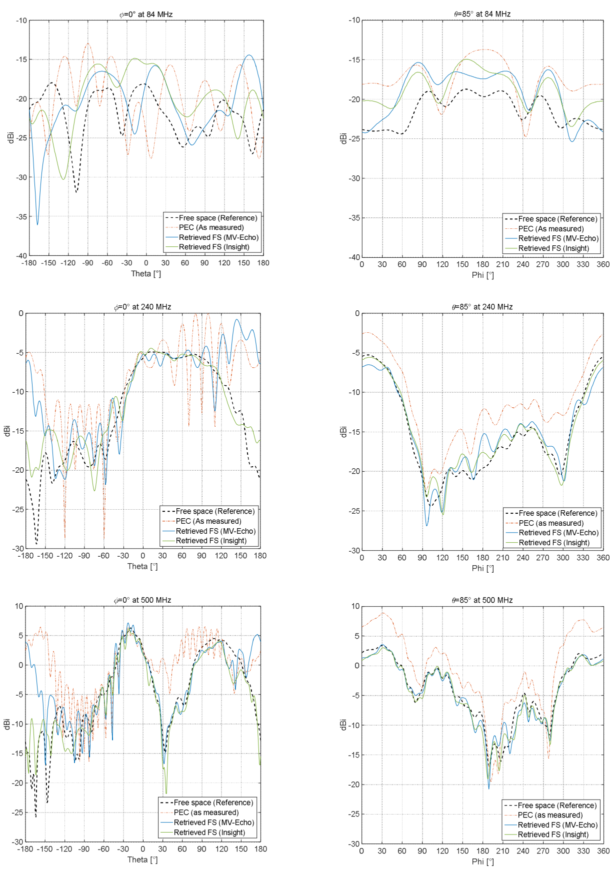

Figure 6. Elevations (first column) and azimuth (second column) gain pattern comparison with the vehicle raised from the floor.

B. Vehicle on the floor

The same pattern comparison shown in the previous section is repeated in Figure 7, considering this time the measurements of the scaled vehicle placed at floor level. Also, in this case, the deviations between the free-space and the "raw" PEC-based measurements are very large. As can be seen, MV-Echo (blue traces) in this case is not capable to effectively remove the impact of the metallic floor, and only in reduced angular regions does the retrieved FS pattern agree well with the reference. The car and its image are now electrically very close, and their contributions are not well separated in the spherical mode domain, hence poor performances are obtained with the modal filtering. In comparison, the performances obtained with Insight are much better at all the analyzed frequencies. Surprisingly, at 84 MHz the performance of the EQC technique are even better than in the previous case when the car was raised from the floor. As explained before, such better results obtained with Insight are due to the fact that a reconstruction geometry closer to the vehicle can be defined, allowing for a more effective filtering and thus also better rejection of the image.

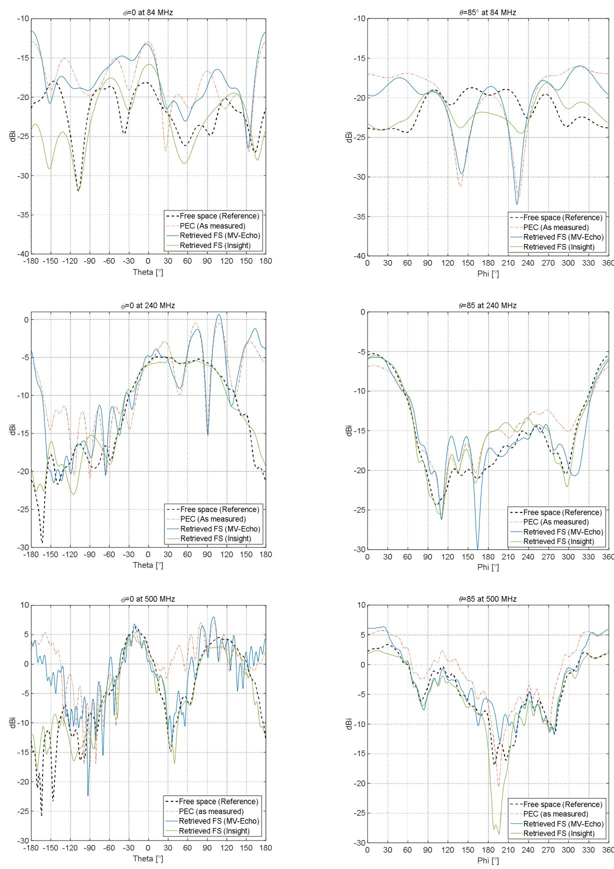

Figure 7. Elevations (first column) and azimuth (second column) gain pattern comparison with the vehicle on the floor.

C. Comparison of different vehicle heights

The different measurement configurations and techniques are compared over the whole frequency band, considering two figures of merit:

- the average gain evaluated on the azimuth cut at θ=85°;
- the Equivalent Noise Level (ENL) evaluated over the 100° angular elevation range (from the zenith down to 10° below the horizon), and on the full azimuth range.

The ENL is defined by the following expression,

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

where $E(\theta,\varphi)$ is the reference and $\tilde{E}(\theta,\varphi)$ is the test pattern.

The average gain comparison over frequency is shown in Figure 8. The black trace is the reference averaged gain obtained in free-space. The solid and dashed orange traces are the averaged gain of the raw PEC-based measurements with the car in "raised" and "floor" configuration, respectively. The interaction with the metallic floor generates up to 5 dB of deviation with respect to the free-space scenario. The blue-solid trace is the averaged gain of the retrieved FS with MV-Echo for the raised vehicle configuration. Such gain agrees very well with the reference, with a maximum deviation of 1.5 dB and 0.5 dB respectively, below and above 240 MHz. Larger deviations are instead obtained if MV-Echo is applied to the PEC-based measurements of the vehicle placed on the floor (see blue-dashed trace). The average gains of retrieved FS with Insight are indicated by the green "x" markers and yellow "+" markers respectively, for the raised and floor configurations. The deviations from the reference are very small.

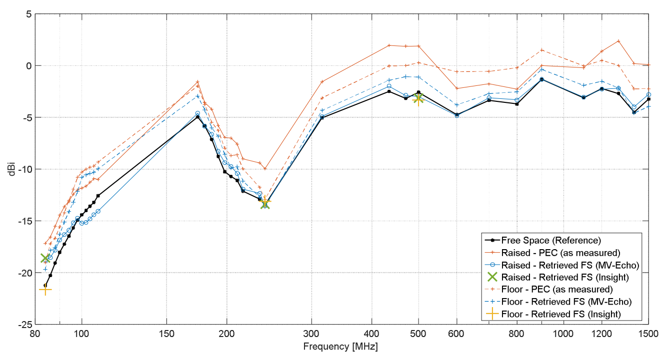

Figure 8. Averaged gain at $\theta = 85°$ over frequency.

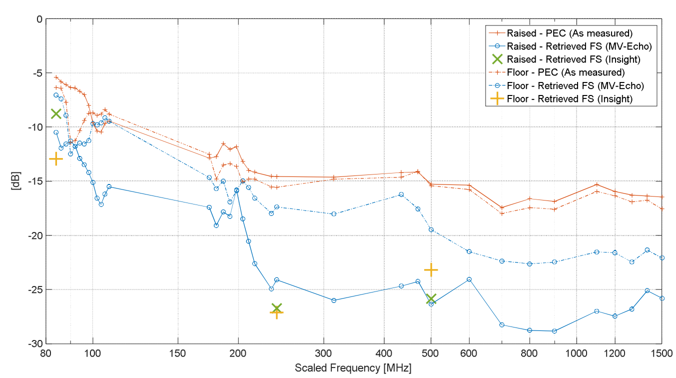

Figure 9. Equivalent noise level over frequency (lower levels correlates better than higher levels).

The ENL over frequency obtained in the different "height" configurations with the considered processing tools is shown in Figure 9. The free-space pattern has been used as reference $E(\theta,\varphi)$ in ENL formula. The reported traces follow the same color/shape nomenclature of the ones used in Figure 8 for the average gain. It can be easily observed that the correlation between the free-space reference and the PEC-based measurements in raised configuration is significantly improved when both the spatial filtering techniques are applied. The ENL is, as expected, much lower at higher frequencies because the electrical separation of the scaled vehicle from floor is larger and thus the applied techniques are more effective. Instead, in the case of the floor configuration, it is (again) observed that the floor cancellation is much more effective if Insight is used.

In general, it is observed that the EQC technique allows for better rejection of the metallic floor, either with the vehicle in the raised or floor configuration. The price to be paid for such better performances is a higher computational time. The EQC technique implemented in Insight is based on an inverse Method of Moments (MoM) [10], whose computational cost increases according to the dimension of the problem with respect to the wavelength. Using a standard laptop, the Insight processing time for the considered cases was around one minute at 84 MHz, and approx. 14 minutes at 500 MHz. Conversely, the SWE implemented in MV-Echo takes advantage of the Fast Fourier Transform (FFT), strongly reducing the computational cost and processing time (less than one minute for all the considered frequencies).

V. CONCLUSIONS

In this paper the effectiveness of two spatial filtering techniques for the removal of the conductive (PEC) floor in automotive measurements have been studied experimentally, and the results compared. The considered techniques are spherical modal filtering and the equivalent currents (EQC), implemented in the commercially available MV-Echo and Insight tools, respectively. A scaled PEC-based automotive measurement scenario has been implemented considering a 1:12 scaled car model, and the StarLab18GHz spherical multiprobe system, where a large metallic floor has been included for the sake of the test. Two different distances, with respect to the floor, of the scaled vehicle have been considered in order to verify the benefits of increasing the electrical distance of the device from the floor. Reference free-space measurements have also been performed without the metallic floor. The investigated frequency range is 84 – 1500 MHz.

It has been shown that by raising the car 7.5 cm (which scales to 0.9 m) from the metallic floor, good rejection of the floor can be obtained with MV-Echo, especially at higher frequencies (> 200-240 MHz) where the electrical separation of the car from the floor is larger. With the same configuration, a similar rejection is also obtained by using Insight. However, it has been shown that the latter tool performs much better on the lower hemisphere.

The same comparison has also been carried out considering the vehicle at floor level. In this case, some limitations of the spherical modal filtering technique have been observed. In contrast, by using the EQC technique, the retrieval of the free-space response is good, despite the reduced electrical distance, and thus the stronger coupling of the car with the floor. This is due to the fact that, with the EQC a finer spatial filtering window with respect to MV-Echo (box instead of a sphere/cylinder) is used, allowing for a better rejection of the metallic floor.

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