Estimation of the Realistic Ground Effect in Free-Space Automotive Measurements

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***Abstract*—Testing of automotive antennas are commonly performed in large Spherical Near Field (SNF) ranges [1-3] able to host the entire vehicle to test the effect of the antenna coupling with the structure [3]. The impact of a realistic ground, such as asphalts or soil, on the radiation performance of the vehicle mounted antennas is often a desired information. As long as the free-space response of the vehicle is available, such information can be obtained with fairly good accuracy considering post-processing techniques based on the Image Theory (IT). Automotive systems with absorber material on the floor [3] are thus ideal for estimating such effects because the free-space signature of the vehicle is directly measured and because the radiation pattern is usually available on more than just a hemisphere.**

In this paper an IT-based technique which allows for the estimation of a realistic ground is proposed and validated with simulations where the measurement setup of a typical multi-probe free-space automotive system is emulated. The impact of the truncation of the scanning area is analyzed in detail showing how advanced post-processing techniques [4-6] can be involved to mitigate the truncation errors and thus obtain a better estimation of the realistic ground effect.

I. Introduction

The testing of automotive antennas is commonly performed in Spherical Near Field (SNF) ranges [1-3]. To include the effect of antenna coupling with the structure, measurements are typically performed considering the entire vehicle [3]. Other than the radiation performance of the antenna mounted on the vehicle, the impact of a real generic ground such as asphalts or soil is often a desired additional information.

Common implementations of automotive measurement systems are based on hemispherical or truncated spherical near-field measurements in which the vehicle is placed on a conducting or absorbing surface. To obtain the correct response of the vehicle with realistic ground parameters, measurement should be performed on different type of grounds. However, this is often unfeasible due to economical and practical constraints. The conducting and absorbing ground conditions represents two extremes in ground parameters. The conducting ground is far from being representative of realistic automotive environment such as asphalts that is strongly dielectric [7]. The fully absorbing ground is generally the preferred solution as the free-space condition is closer to realistic grounds but nevertheless is an approximation [7].

In recent publications, the response of an antenna to different operational environments is found by combining the measurement of the stand-alone antenna with a simulation of the ground or surrounding structure. This solution has been applied to antenna placement problem [8-10] showing that the accuracy of the method depends on having a good approximation of the correct local boundary condition when performing the measurement. In the case of a flat surface, such as in most automotive applications, the procedure is reduced to a direct application of Image Theory (IT) that can be implemented directly on the radiation pattern or on the spherical wave coefficients [10].

Automotive systems described in [3] are ideal for estimating different ground effects using this IT-based method because the absorbing floor emulates the free-space condition which is electromagnetically closer to realistic grounds and because the radiation pattern is available on more than just a hemisphere. In this paper the applicability of this method in case of free-space automotive system like the one shown in Figure 1. will be demonstrated considering a realistic automotive scenario.

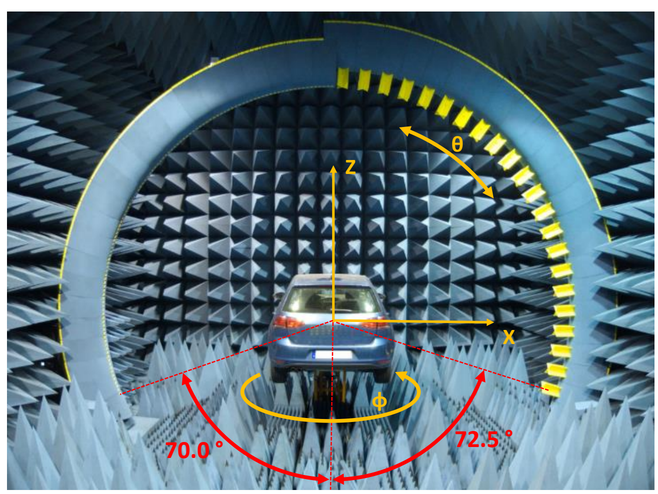

Figure 1. Multi-probe, Automotive Range at Ilmenau from MVG covering the 70 MHz to 6 GHz range.

II. Application of the Ground Plane Properties

In most of the automotive application the antenna mounted on the vehicle is operating on a flat surface (asphalts or soil). The behaviour of Device Under Test (DUT) in its final environment could be evaluated from the free-space measurements of the DUT by emulating the effect of the ground applying the Image Theory (IT) [11]. The image of the DUT is in this case weighed accordingly to the electrical property of the ground material. For simplicity, the case of a horizontal plane, with normal direction $\hat{n} = \hat{z}$ (located at z=0) as the interface between two materials, is considered (Figure 2.).

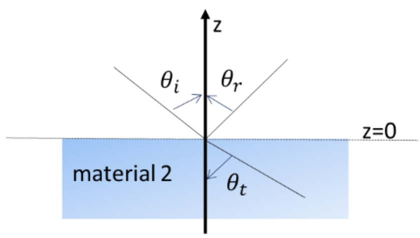

Figure 2. Image principle.

The reflected field (E_θ^r, E_ϕ^r) is defined from the incident field (E_θ^i, E_ϕ^i) at the interface by,

$$\begin{bmatrix} E_\theta^r \\ E_\phi^r \end{bmatrix} = \begin{bmatrix} \Gamma_h & 0 \\ 0 & \Gamma_s \end{bmatrix} \begin{bmatrix} E_\theta^i \\ E_\phi^i \end{bmatrix} \quad (1)$$

where Γ_h and Γ_s are the are the orthogonal (hard) and parallel (soft) reflection coefficients. The reflection coefficients (Γ_h, Γ_s) in (1) are defined by,

$$\Gamma_h = \frac{Z_o cos\theta_i - Z_{eq} \cos\theta_t}{Z_o cos\theta_i + Z_{eq} \cos\theta_t} \qquad \Gamma_s = \frac{Z_{eq} \cos\theta_i - Z_o cos\theta_t}{Z_{eq} \cos\theta_i + Z_o cos\theta_t} \quad (2)$$

where θ_i is the incidence angle formed by the unit normal vector $\hat{n}$ of the reflecting surface and the incidence direction; θ_t is the transmission angle; Z_{eq} is the equivalent impedance of the reflecting surface and Z_0 is the free-space impedance.

The equivalent impedance is defined by,

$$Z_{eq} = Z_o \sqrt{\frac{\mu_r}{\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o}}} \quad (3)$$

where $Z_o = 120\pi$ is the free-space impedance, ε_r the relative permittivity and σ the conductivity.

The transmission angle is defined by,

$$cos\theta_t = \sqrt{1 - \left(\frac{k_o}{k_{eq}}\right)^2 sin\theta_i^2} \quad (4)$$

where k_{eq} is the equivalent material wave number,

$$k_{eq} = k_o \sqrt{\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o}\right)\mu_r} \quad (5)$$

If the material is a perfect electric conductor (PEC), Γ_h = 1 and Γ_s=-1 [10-11].

In the technique proposed in this paper the image theory is exploited by simply mirroring the FF with respect to the ground interface and weighting it according to the above reported reflection coefficients. The obtained image is then superimposed to the original data obtaining a resulting field valid on the forward hemisphere [10].

As an example, the emulation of two types of ground plane materials from a free-space measurement is reported in the following. The DUT is a broadband patch antenna mounted on the rear hood of a 1:12 scaled vehicle model. The DUT has been measured in the MVG StarLab spherical near field multi-probe system as shown in Figure 3. in the frequency band 1.1-18GHz, corresponding to the 91.7–1500.0 MHz scaled frequency range.

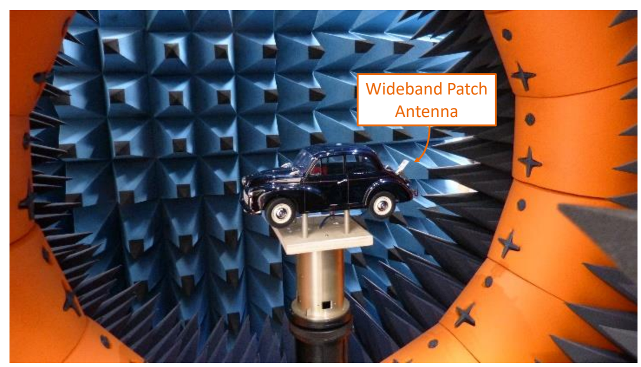

Figure 3. 1:12 scaled car model during measurement in the MVG StarLab multi-probe system.

Two ground types have been emulated: asphalt, with relative permittivity $\varepsilon_r = 4.61$ and conductivity $\sigma = 0\ S/m$, and soil with $\varepsilon_r = 2.25$ and $\sigma = 0.16\ S/m$ [7]. The gain pattern comparison at 1.5 GHz (scaled frequency) for the averaged azimuth cut in the $\theta = [70° - 90°]$ range is reported in Figure 4. for free-space (blue trace), asphalt (orange trace) and soil (green trace). As can be seen the gain level increases of approx. 2.5 dB when the two grounds are considered.

The modification of the radiating performances due to the presence of the ground, such as the ones observed in Figure 3. by applying the IT-based technique, are a very interesting and desired information. In the following sections the accuracy of the proposed technique will be investigated taking into account a simulated automotive scenario, where the realistic measurement conditions of a free-space multi-probe automotive system are emulated [3].

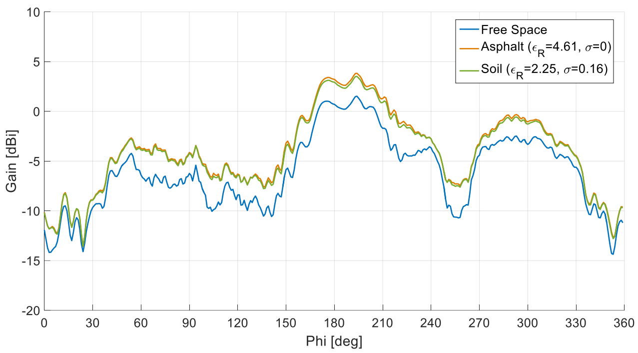

Figure 4. Gain pattern comparison at 1.5 GHz on the averaged azimuth cut in the θ = [70°- 90°] range.

III. FREE-SPACE AUTOMOTIVE MEASUREMENTS

To fully characterize the radiating properties of the vehicle mounted antennas, a large measurement system capable of accommodating the full vehicle is required. However, due to vehicle size, weight and/or economic factors, a full spherical scan is often unfeasible. For this reason, truncated spherical scanners are typically preferred.

Automotive systems described in [3] are ideal for estimating different ground effect, because the absorbing floor emulates the free-space condition which is electromagnetically closer to realistic grounds and because the radiation pattern is available on more than just a hemisphere. An example of such system is reported in Figure 1. where the multi-probe automotive spherical NF system installed at the Ilmenau University and provided by Microwave Vision Group (MVG) is shown.

When the standard NF/FF transformation is applied to a truncated Spherical Near Field (SNF) dataset, the resulting FF pattern is generally affected by errors [4-6]. In fact, in such cases the NF/FF transformation is typically performed by filling the missing portion of the sphere with zeros (Zero-Padding, ZP) resulting in a discontinuous NF. To represent such a discontinuous field in the spherical wave domain, a very large number of spherical wave functions is needed (ideally an infinite number). Due to the cut-off properties of the Spherical Wave Expansion (SWE) [2], the highest spherical wave mode order is given by

$$N_{max} = k\, R_{meas} = \frac{2\pi f}{c} R_{meas} \qquad (6)$$

where k is the wavenumber, c is the free-space speed of light, f is the frequency and R_{meas} is the radius of the measurement sphere. For a given and finite R_{meas}, the total number of computable spherical modes becomes bigger when the frequency is increased. As shown in [6], truncation errors are thus less important at higher frequencies because the discontinuity introduced by the zero-padding of the NF can be represented by a larger number of spherical wave modes.

To mitigate the truncation error in free-space automotive SNF two techniques have been proposed in previous publications [4-6].

The first technique is the Iterative Model Filtering (IMF) [4-6] and is based on the SWE of the measured field which is applied iteratively. At each iteration a modal filtering based on the DUT minimum sphere is applied cancelling out the higher order spherical modes introduced by the truncation. The filtered spherical wave coefficients are then used to extrapolate the NF on the truncated area which is then combined with measured NF in order to obtain a full spherical NF dataset. This process is repeated until the filtered NF data corresponds to the measured NF data on the measurement sphere within a given threshold. The method is very computational efficient and works well as long as there are enough NF samples to be able to take advantage of the modal filtering.

The second technique is based on the EQuivalent Current (EQC) expansion [5-6]. During the EQC expansion, the measured NF data is used directly disregarding the truncated zone. The EQC expansion is in fact a minimum energy operator on the truncated region, which allows for a direct computation of the currents avoiding errors caused by the processing of a discontinuous field.

IV. EMULATION OF A REALISTIC FREE-SPACE AUTOMOTIVE SCENARIO

To validate the proposed approach, a realistic free-space automotive scenario has been emulated. An Inverted-F antenna (IFA) mounted on the front bumper of a car has been simulated with a full-wave tool [12]. The simulated car model is shown in Figure 5. The maximum dimension of the vehicle are [L x W x H] ~ [4.5 x 2.0 x 1.4]m and the working frequency is 600 MHz. Two scenarios have been simulated:

- Free-Space on the full-sphere;
- Infinite asphalt (ε_r=4.61, σ=0) on the forward hemisphere;

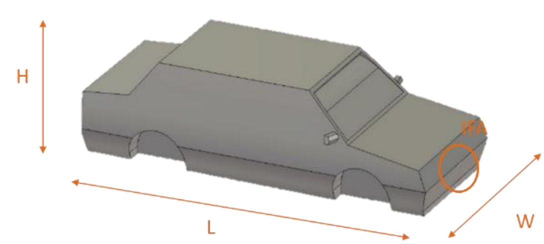

Figure 5. Simulated car model and dimensions.

The simulation over the infinite asphalt have been considered as reference in the test. The one in free-space have instead been used to emulate the same measurement conditions of the Ilmenau multi-probe range shown in Figure 1. Such range is characterized by two truncated arches working respectively in 70-400 MHz and 0.4-6 GHz frequency range. According to the considered frequency, the properties of the HF arch have been reproduced computing the NF over a 4m radius sphere, with 1° sampling step and a maximum elevation angle of θ = 110°. In order to maximize the validity area of the resulting pattern, the vehicle has been located at the maximum height allowable by the system being Z=-40cm. A sketch of the simulated scenario is illustrated in Figure 6.

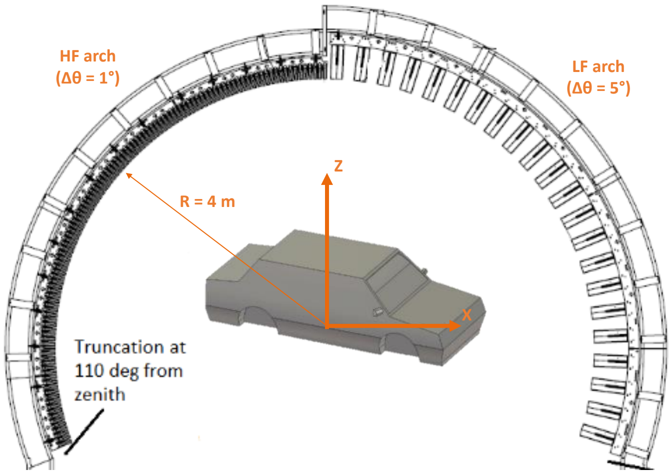

Figure 6. Sketch of the emulated measurement scenario in the free-space multi-probe automotive range at Ilmenau.

V. VALIDATION RESULTS

As a first step in the validation of the proposed approach the previously described truncation error mitigation techniques have applied to the SNF dataset and compared to the conventional NF/FF with zero-padding and the free-space pattern not affected by truncation errors. Such comparison is reported in Figure 7. for the elevation pattern cut at φ = 90°. The blue trace is the free-space pattern without truncation while the yellow, green and orange traces are the patterns obtained from the emulated SNF applying NF/FF with zero-padding, IMF and EQC techniques, respectively. The shadowed areas are associated to the truncated region. When the zero-padding is applied a ripple is introduced all over the pattern and significantly large errors are obtained in proximity of the truncation angle ($|\theta| = [100° - 110°]$). As can be seen such errors are strongly reduced applying the two truncation error mitigation techniques.

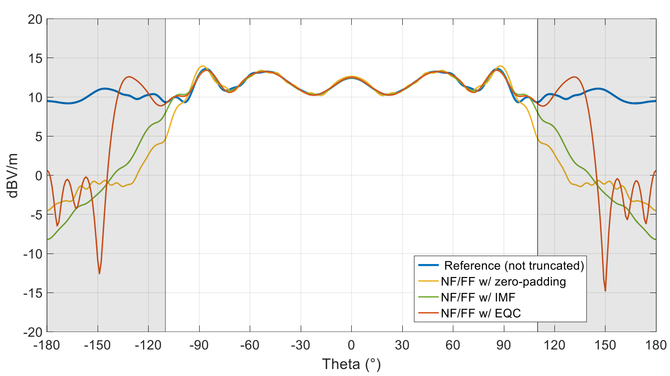

Figure 7. Elevation pattern comparison at φ = 90° before the application of the ground properties.

The ground properties (asphalt) have been applied in a second step with the proposed IT-based technique. It is remarked that, even without any truncation, when the such technique is applied the processed field is valid only in the forward hemisphere. This is a direct consequence of the image theory. The truncation at θ = 110° imposes a further reduction of the validity angular region which is finally ranging from θ = 70° to θ = 90° as shown by the green area in Figure 8. To not further reduce such validity angular region, it is remarked the importance of having accurate FF data in proximity of the truncation angle which can be achieved applying the two truncation error mitigation techniques here involved.

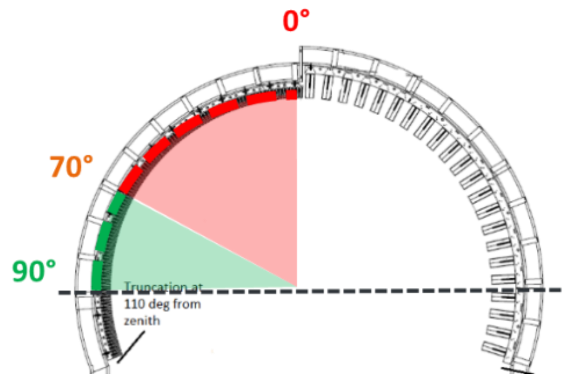

Figure 8. Validity angular region of the emulated measurement after the application of the ground properties with the IT-based technique.

The retrieved car response over asphalt have been computed applying the IT-based technique to the FF data obtained with different truncation error mitigation techniques. Of course, a proper translation of the reference system has been considered in order to place ground floor at the level of the wheels. The obtained results are then compared with the reference obtained simulating the car over the asphalts.

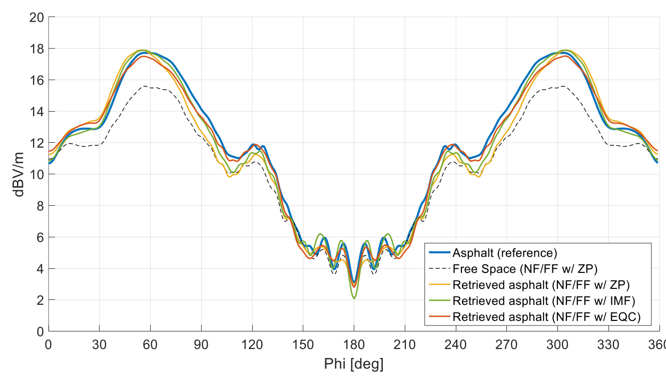

Figure 9. Comparison on the averaged azimuth cut in the θ = [70°- 90°] range after the application of the ground properties with the IT-based technique.

The comparison on the averaged azimuth cut in the $\theta = [70° - 90°]$ is shown in Figure 9. Blue trace is the reference; yellow, green and orange traces are obtained applying the asphalt ground properties on the NF/FF transformed data with zero-padding, IMF and EQC techniques, respectively. In the same plot the free-space response obtained from the simple

NF/FF transformation of the emulated measurement is also reported (see black dashed trace). As can been seen the peak of the free-space pattern is approx. 2 dB lower than the reference. Instead, applying the proposed technique it has been possible to retrieve the radiating performance of the vehicle over the asphalt with good accuracy. In particular, the comparison shows better performance when the IMF and EQC techniques are applied for the treatment of truncation.

The accuracy of the presented results is also evaluated considering the Equivalent Noise Level (ENL) defined by equation (7) where, $E(\theta,\varphi)$ is the reference pattern and $\tilde{E}(\theta,\varphi)$ is the test pattern.

$$ENL = 20\log_{10}\left(RMSE\left|\frac{E(\theta,\varphi) - \tilde{E}(\theta,\varphi)}{E(\theta,\varphi)_{MAX}}\right|\right) \qquad (7)$$

The ENL is evaluated considering again as reference the pattern simulated on the asphalt. The metric has been evaluated on the same averaged azimuth cut previously shown and is reported Table I. The ENLs obtained emulating the asphalt with the IT-based technique shows a relevant improvement with respect to the free-space approximation. Furthermore, as commented above, the more advanced NF/FF technique used to mitigate the truncation errors of the automotive system allow for a better agreement with the reference.

TABLE I. RESULT ACCURACY

Data Processing	**ENL (dB)**
Free Space (NF/FF w/ ZP)	-19.0
Retrieved Asphalt (NF/FF w/ ZP)	-25.3
Retrieved Asphalt (NF/FF w/ IMF)	-30.6
Retrieved Asphalt (NF/FF w/ EQC)	-30.3

VI. CONCLUSIONS

Free-space automotive measurements are ideal for estimating the effect of different grounds, because the absorbing floor is electromagnetically closer to realistic grounds and because the radiation pattern is available on more than just a hemisphere.

The proposed image-based technique has been validated with simulations where the realistic measurement conditions of a multi-probe free-space automotive system have been emulated. In particular, the truncation of the scanning area has been introduced at 20° below the horizon as in the automotive system at the Ilmenau University. In order to mitigate the truncations errors, the IMF and EQC advanced post-processing techniques have been applied and compared to the conventional NF/FF transformation performed with zero-padding.

It has been demonstrated that a good estimation of realistic ground floors (in this case asphalt) can be obtained up to 20° above the horizon applying the proposed IT-based technique to truncated free-space automotive measurements. The accuracy of the estimated pattern is improved when truncation error mitigation techniques are used before the application of the IT-based technique.

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