URSI GASS 2020, Rome, Italy, 29 August - 5 September 2020

A Non-Redundant Hemi-Spherical Scanning for Automotive Antenna Near-Field Measurements

F. Ferrara(1), C. Gennarelli(1), R. Guerriero* (1), and G. Riccio(2)
(1) D.I.In. – University of Salerno, Fisciano (SA), Italy
(2) D.I.E.M. – University of Salerno, Fisciano (SA), Italy

Abstract

A non-redundant sampling representation of the probe voltage is proposed to reduce the number of needed near-field data for hemi-spherical antenna measurements in an automotive testing set-up with a flat metallic ground. This last is taken into account by employing the image principle. The approach benefits from a useful modeling of the radiating system including many RF sub-systems and the host vehicle. An adaptable convex surface containing the entire radiating system and its image is chosen as source modeling and the optimal parameters are determined for applying the corresponding sampling and interpolation algorithms. Accordingly, the procedure allows one to reconstruct the voltage values on the near-field hemi-sphere from the knowledge of a minimum number of data. It is obvious that the reduction of the collected data implies a saving of the acquisition time in the testing process.

1 Introduction

Today all media offer advertisements in which modern vehicles are increasingly dependent on wireless systems and services. As a consequence, more and more antennas are highly integrated with the automotive body for aesthetic, practical and performance reasons. For example, they must guarantee communications with other vehicles to avoid collision, with terrestrial infrastructures for incident warning, and with satellites for monitoring the vehicle status.

Each antenna is usually designed by including small sections of the surrounding structure where it must be mounted, since the total automotive body cannot be simulated accounting for all its geometrical and material characteristics. However, body and shape of the vehicle affect the antenna performance when transmitting and receiving. This leads to an increasing demand for testing the antenna when this last is installed and, therefore, the device under test (DUT) is not the antenna alone, but the complete vehicle. Measurements in near-field (NF) or far-field (FF) DUT range can be used to this end. In particular, a hemi-spherical NF scanning has been recently considered for automotive antenna testing [1]-[3] by placing the DUT on a turntable and moving the probe on a fixed arc or by mounting the probe on a rotating arm. The NF data are collected above a metalized ground to obtain a well-controlled environment, which guarantees a good repeatability of the measurements, but the knowledge of such data is inadequate to take advantage of the spherical NF to FF (NFTFF) transformation technique [4]. On the other hand, the missing NF data on the lower hemi-sphere can be determined by applying the image principle for a perfectly conducting (PEC) ground to the measured NF samples on the upper hemisphere [1]-[3]. This enables the data mapping on the full NF sphere and the spherical NFTFF transformation.

Obviously, the number of measured NF samples is crucial to optimize the scanning time, which is considerably longer than the required post-processing time. Such a number can be reduced by adopting a non-redundant sampling representation [5] based on a proper choice of the DUT modeling. An Optimal Sampling Interpolation (OSI) algorithm can permit the data evaluation at each point on the scanning domain from the knowledge of such a non-redundant number of samples. Effective spherical NFTFF transformations properly exploiting these theoretical results have been developed in [6] and [7].

The goal of this research paper is to propose a non-redundant sampling representation of the probe voltage on the hemi-spherical scanning surface. The data are collected on parallels having a variable angular distance from the close ones. Moreover, the number of samples is not the same on each parallel, but decreases when moving towards the pole. The position of the parallels and the location of the sampling points on them are determined according to a useful adaptable convex surface containing the DUT and its image. Accounting for the geometry of the vehicle, a good choice for the DUT modeling is an upside-down bowl with the base placed at the roof of the vehicle and the aperture on the ground plane (see Fig. 1). Accordingly, the full source modeling is formed by the DUT bowl and its image. The corresponding OSI algorithm is also presented and applied for mapping the data on the half-sphere.

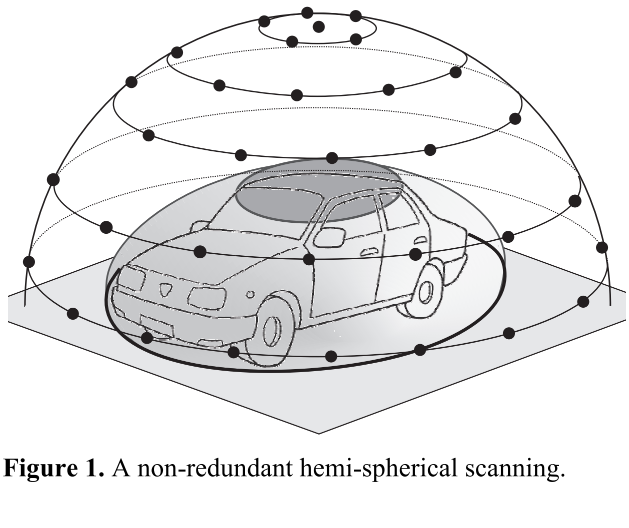

Figure 1. A non-redundant hemi-spherical scanning.

2 Non-Redundant Voltage Representation

Let us suppose that the metalized ground plane of a hemispherical NF set-up is a PEC ground plane of infinite extension along the *x* and *y* directions and assume that the origin *O* of the adopted spherical coordinate system (r, ϑ, φ) lies on it. Moreover, let us also suppose that the used probe is electrically small and exhibits a first order azimuthal dependence (first-order probe). As shown in [8], such a kind of probe has almost the same effective spatial bandwidth as the DUT field.

The given problem can be reformulated by removing the infinite PEC ground plane and mirroring the given DUT with respect to the plane $z = 0$. The application of the non-redundant sampling representations of EM fields [5] requires to fulfill the following conditions: *i*) to consider the radiating source as contained in the smallest rotational surface Σ, *ii*) to adopt a proper parameterization $\underline{r} = \underline{r}(\xi)$ to represent each of the curves (meridians and parallels) describing the spherical surface of radius *d*, and *iii*) to introduce the "reduced voltage" $\tilde{V}(\xi) = V(\xi)\,\mathrm{e}^{\mathrm{j}\psi(\xi)}$ obtained by multiplying the voltage expression *V* of the probe (V_p) and rotated probe (V_r) by a proper phase factor $\mathrm{e}^{\mathrm{j}\psi(\xi)}$. As shown in [5], $\tilde{V}(\xi)$ is well approximated by a function band-limited to $\chi' W_\xi$, $\chi' > 1$ being an excess bandwidth factor needed to control the band-limitation error. If the DUT is considered as enclosed in an upside-down bowl, Σ is a "double bowl", formed by the DUT bowl and its image. The radius of the circular aperture at $z = 0$ is denoted by *a* and the curvature radius of the lateral bends is *c* (see Fig. 2).

When the observation curve is a meridian, the bandwidth, the parameter, and the related phase function are [7]:

$$W_\xi = \beta \ell' ; \qquad \xi = (\pi/\ell')\left[R_1 - R_2 + s_1' + s_2'\right] \tag{1}$$

$$\psi = (\beta/2)\left[R_1 + R_2 + s_1' - s_2'\right] \tag{2}$$

where β is the wavenumber, $\ell' = 4(a-c) + 2\pi c$ is the length of the curve C' obtained as intersection between the meridian plane passing through the observation point *P* and Σ, $s_{1,2}'$ are the curvilinear abscissas of the two tangency points $P_{1,2}$ on C', and $R_{1,2}$ the distances from *P* to $P_{1,2}$. The values of $R_{1,2}$ and $s_{1,2}'$ change depending on the positions of $P_{1,2}$ [7].

On a parallel at $\vartheta(\xi)$, the phase function results to be constant, the azimuthal angle φ can be chosen as optimal parameter, and the corresponding bandwidth [7] is:

$$W_\varphi = \frac{\beta}{2} \max_{z'} \left(R^+ - R^-\right) = \frac{\beta}{2} \max_{z'} \left(\sqrt{(z-z')^2 + \left(\rho + \rho'(z')\right)^2} + \right.$$
$$\left. - \sqrt{(z-z')^2 + \left(\rho - \rho'(z')\right)^2} \right) \tag{3}$$

where $\rho'(z')$ is the equation of Σ, $\rho = d \sin\vartheta$, and the maximum is attained on the upside-down bowl. To this end, it is opportune to consider the angle η such that $z' = c\cos\eta$

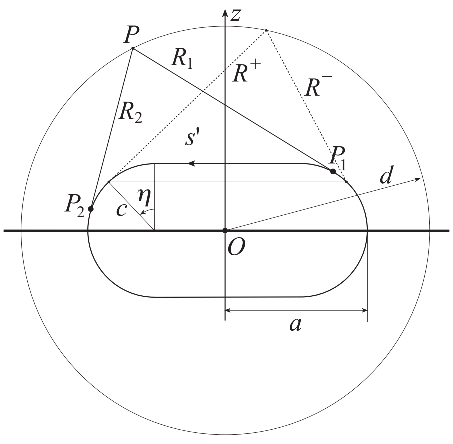

Figure 2. Relevant to the double bowl DUT modeling.

and $\rho' = (a-c) + c\sin\eta$. It has been found [7] that the maximum is attained at the η value zeroing the derivative of $R^+ - R^-$.

The above non-redundant representation allows one to set the sampling arrangement over the whole observation sphere. However, due to the presence of the infinite PEC ground plane, only the knowledge of the NF samples over the upper hemi-sphere is practically possible. Fortunately, as a result of the image principle, the NF samples on the lower hemi-sphere can be properly synthesized from those acquired on the upper one by applying the following "mirroring rule"

$$\begin{cases} V_p\left(r, \pi - \vartheta, \varphi\right) = -V_p\left(r, \vartheta, \varphi\right) \\ V_r\left(r, \pi - \vartheta, \varphi\right) = V_r\left(r, \vartheta, \varphi\right) \end{cases} \tag{4}$$

Relations in (4) stay valid for the considered first-order probe. Accordingly, the voltage values can be accurately reconstructed without truncation error at any point of the upper hemi-sphere by means of the following 2-D OSI scheme obtained by properly matching the OSI expansions along meridians and parallels:

$$V(\xi(\vartheta), \varphi) = \mathrm{e}^{-\mathrm{j}\psi(\xi)} \sum_{n=n_0-q+1}^{n_0+q} \left\{ \Omega_N\left(\xi - \xi_n, \bar{\xi}\right) D_{N''}^{e}\left(\xi - \xi_n\right) \cdot \right.$$
$$\left. \sum_{m=m_0-p+1}^{m_0+p} V\left(\xi_n, \varphi_{m,n}\right) \mathrm{e}^{\mathrm{j}\psi(\xi_n)}\, \Omega_{M_n}\left(\varphi - \varphi_{m,n}, \bar{\varphi}\right) D_{M_n''}\left(\varphi - \varphi_{m,n}\right) \right\} \tag{5}$$

where $2p$ and $2q$ are the numbers of the closest voltage samples $V(\xi_n, \varphi_{m,n})$ retained in the interpolation along the azimuthal circumferences and the meridian curve through *P*, respectively, $n_0 = \lfloor \xi/\Delta\xi \rfloor$, $m_0 = \lfloor \varphi/\Delta\varphi_n \rfloor$ the indexes of the voltage sample closest (on the left) to *P*,

$$\xi_n = n\Delta\xi = \pi n / N'' ; \qquad N'' = \lfloor \chi N' \rfloor + 1 \tag{6}$$

$$N' = \lfloor \chi' W_\xi \rfloor + 1 ; \quad N = N'' - N' ; \quad \bar{\xi} = q\Delta\xi \tag{7}$$

$$\varphi_{m,n} = m\Delta\varphi_n = 2\pi m / (2M_n'' + 1) ; \quad M_n'' = \lfloor \chi M_n' \rfloor + 1 \tag{8}$$

$$M'_n = \lfloor \chi^* W_\varphi(\xi_n) \rfloor + 1 \; ; \qquad M_n = M''_n - M'_n \tag{9}$$

$$\chi^* = 1 + (\chi' - 1)\,[\sin\vartheta(\xi_n)]^{-2/3} \; ; \qquad \bar{\varphi} = p\,\Delta\varphi_n \tag{10}$$

$\lfloor x \rfloor$ denoting the integer part of x, and $\chi > 1$ being an over-sampling factor to be used for the control of the truncation error [5], [7]. Moreover, $D_{L''}(\sigma)$ is the Dirichlet function for an odd number of samples,

$$D^e_{L''}(\sigma) = \frac{2L''-1}{2L''} D_{L''-1}(\sigma) \tag{11}$$

is that for an even number of samples, and $\Omega_L(\sigma, \bar{\sigma})$ is the Tschebyscheff sampling function [5]. Note that the OSI expansion along the meridians is tailored for an even number of samples, since the distribution of the sampling parallels has to be symmetrical with respect to the plane $z = 0$ to make possible the mirroring of the acquired voltages according to the rule (4). Moreover, N'' is enforced to be an odd number to skip the measurements on the PEC ground plane.

The 2-D OSI formula (5) can be properly employed to reconstruct the NF data at the spherical sampling grid, which allows one to evaluate the modal expansion coefficients of the DUT field as described in [4]. These last can be substituted in the general spherical wave expansion or in its asymptotic FF formulation to recover the radiated EM field.

3 Numerical Examples

Numerical examples are reported in the following to assess the effectiveness of the proposed non-redundant sampling representation and related 2-D OSI algorithm.

Let us assume a standard sedan car having the following dimensions: length l = 4.2 m, width w = 1.8 m and height h = 1.8 m. To simulate potential distributed sources matching the sedan car dimensions, a rectangular planar array with area $l \times w$ has been located at 1.2 m from the ground. The array elements have been fed at 5 GHz in such a way to have the maximum of the radiated field into the longitudinal section of the car.

According to the car dimensions, the more appropriate DUT bowl modeling has been described by $a = 53\,\lambda$ and $c = 30\,\lambda$, where λ is the free-space wavelength. The probe voltage samples have been simulated as acquired over the upper hemi-sphere with radius $d = 75\,\lambda$ by an open-ended WR187 rectangular waveguide exhibiting a first-order probe feature.

Figures 3 and 4 show representative reconstruction examples of the amplitude and phase of the rotated probe voltage V_r on the cut plane at $\varphi = 0°$. The reconstructions of the amplitude and phase of V_p on the cut plane at $\varphi = 90°$ are reported in Figs. 5 and 6. As can be seen, the reconstructed patterns agree very well with the exact simulated ones and do not suffer from the truncation error. This last occurs if the samples falling over the lower hemi-sphere are zeroed, rather than synthesized via formula (4). For completeness, the reconstructions of the amplitude and phase of V_r in correspondence of the PEC ground plane (ϑ = 90°) are also reported in Figs. 7 and 8. All the reported reconstructions have been obtained by using χ'=1.10, χ=1.20 and $p = q = 9$ to ensure a mean square reconstruction error lower than – 80 dB. Note that, unlike the techniques in [1]-[3], the here proposed approach makes possible to reconstruct the NF data also on the PEC ground plane, wherein a direct acquisition is not possible. The knowledge of these data, otherwise set to

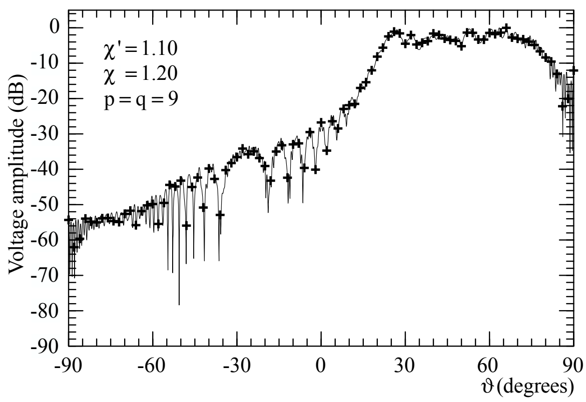

Figure 3. Amplitude of V_r on the cut plane at φ = 0°. Line: exact. Crosses: interpolated.

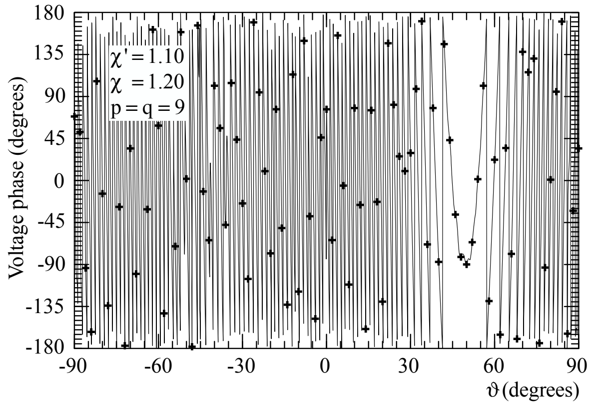

Figure 4. Phase of V_r on the cut plane at φ = 0°. Line: exact. Crosses: interpolated.

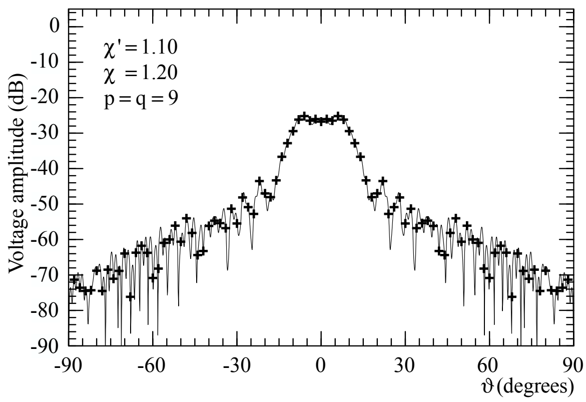

Figure 5. Amplitude of V_p on the cut plane at φ = 90°. Line: exact. Crosses: interpolated.

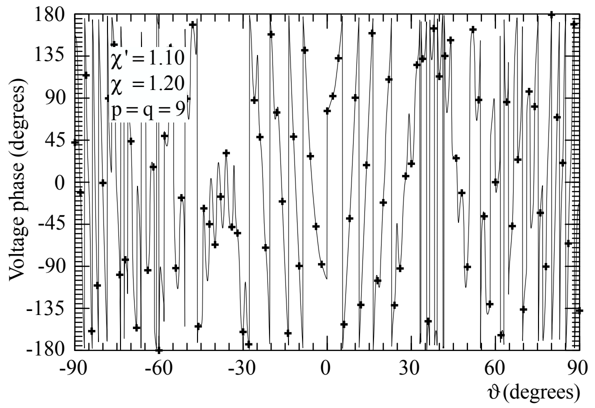

Figure 6. Phase of V_p on the cut plane at φ = 90°. Line: exact. Crosses: interpolated.

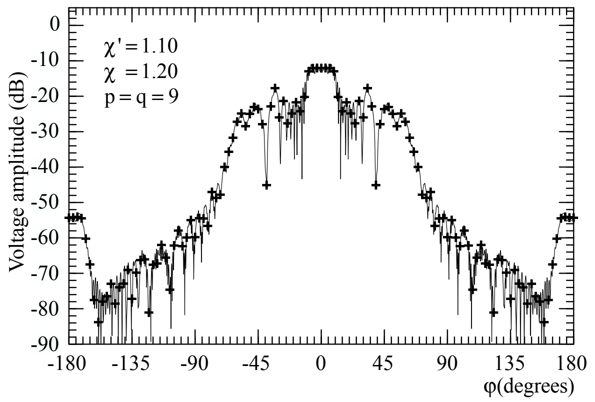

Figure 7. Amplitude of V_r on the PEC ground plane. Line: exact. Crosses: interpolated.

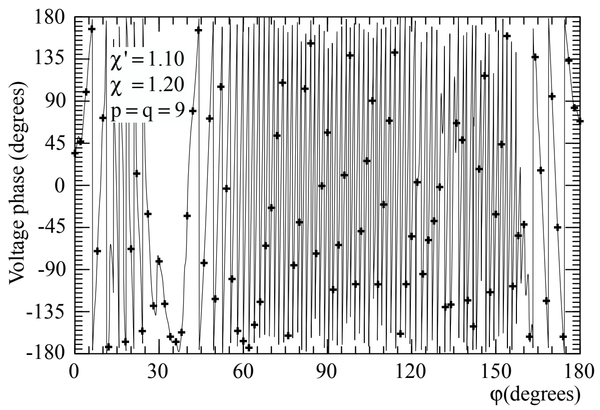

Figure 8. Phase of V_r on the PEC ground plane. Line: exact. Crosses: interpolated.

zero, allows one to obtain all the NF data needed to evaluate the modal expansion coefficients of the DUT field via the probe compensated formulas in [4] and, hence, the radiated EM field. It must be stressed that the number of NF measurements required by the proposed scanning technique is equal to 84550, which is remarkably smaller than that (129600) recommended by the classical approach in [4]. In fact, the number 129600 is related to the radius of the minimum sphere enclosing the DUT plus its image.

4 Conclusions and Future Activities

An efficient NF scanning technique for automotive testing with flat metallic ground has been proposed in this work. It uses a non-redundant sampling representation of the voltage over a hemi-spherical surface and takes advantage on the principle of image to account for the PEC ground plane. An accurate 2-D OSI algorithm allows the reconstruction of the voltage at any point over the upper hemisphere and, in particular, at those required to evaluate the modal expansion coefficients [4]. It is so possible to map the radiated EM field from a reduced number of NF samples. In fact, the number of NF measurements required by the proposed scanning technique results to be remarkably smaller than that recommended by [4]. The future target of the authors is to assess the effectiveness of the proposed technique by means of measurements tests in collaboration with interested industrial partners.

5 References

[1] D.W. Hess and D.G. Bodnar, "Ground plane simulation and spherical near-field scanning for telematic antenna testing," *Proc. of AMTA 2004*, Atlanta, GA, USA, Oct. 2004.

[2] J.R. Camacho-Perez and P. Moreno, "Initial considerations towards hemispherical near-field antenna measurements," *IEEE Antennas Wireless Prop. Lett.*, **13**, 2014, pp. 1441-1444.

[3] R.A.M. Mauermayer and T.F. Eibert, "Spherical field transformation above perfectly electrically conducting ground planes," *IEEE Trans. Antennas Prop.*, **66**, 3, Mar. 2018, pp. 1465-1478.

[4] J. Hald, J.E. Hansen, F. Jensen, and F.H. Larsen, *Spherical near-field antenna measurements*, J.E. Hansen, (ed.), London, Peter Peregrinus, 1998.

[5] O.M. Bucci, C. Gennarelli, and C. Savarese, "Representation of electromagnetic fields over arbitrary surfaces by a finite and nonredundant number of samples," *IEEE Trans. Antennas Prop.*, **46**, 3, Mar. 1998, pp. 351-359.

[6] O.M. Bucci, C. Gennarelli, G. Riccio, and C. Savarese, "Data reduction in the NF–FF transformation technique with spherical scanning," *J. Electromagn. Waves Appl.*, **15**, 2001, pp. 755-775.

[7] F. D'Agostino, F. Ferrara, C. Gennarelli, R. Guerriero, and M. Migliozzi, "Effective antenna modellings for NF–FF transformations with spherical scanning using the minimum number of data," *Int. Jour. Antennas Prop.*, **2011**, 2011, ID 936781, 11 pages.

[8] O.M. Bucci, G. D'Elia, and M.D. Migliore, "Advanced field interpolation from plane-polar samples: experimental verification," *IEEE Trans. Antennas Prop.*, **46**, 2, Feb. 1998, pp. 204-210.