Validation of the Fully Probe Corrected Translated-SWE Algorithm for Spherical Near Field Offset Measurements with Minimum Sampling

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***Abstract*—The Translated Spherical Wave Expansion (TSWE) is a very effective Near-Field-to-Far-Field (NF/FF) transformation tool for down-sampled Spherical Near Field (SNF) measurements with offset Antenna Under Test (AUT). As presented in previous publications, such tool is well suited to characterize antennas mounted on complex structures such as cars, satellites and airplanes. In case of electrically small probes and/or small AUT-probe view angles the TSWE can be accurately applied without compensating for the probe effect. Instead, in case of more complex probes, the measured signal is affected by an averaging effect that should be compensated to ensure a good accuracy. In this paper the TSWE technique with full probe correction capabilities is validated considering measurements of a standard gain horn performed at several frequencies. The horn has been intentionally displaced in an offset configuration and measured in SNF geometry with a first order probe and two different wideband higher-order antennas as probe.**

***Index Terms*—Probe correction, Under-sampling, Spherical Near Field, Spherical Wave Expansion.**

I. Introduction

The advent of modern antenna systems has dramatically increased the complexity of the radiating tests which requires large bandwidth, high accuracy and short measurement time. Antennas might also be strongly coupled with the structures where they are installed (vehicles, satellites, airplanes etc…) thus, the measurement of the full system is often required.

Spherical Near Field (SNF) measurements are a very accurate and well-established testing methodology but, in case of electrically large Antenna Under Test (AUT), they might require long acquisition time due to the large number of NF samples needed to fulfil the Nyquist criteria [1-2]. To reduce the sampling requirements in case of SNF offset measurements, the Translated Spherical Wave Expansion (TSWE) technique has been recently introduced and validated both in case of stand-alone antenna [3] and antenna mounted on a car [4-5].

One aspect that has to be accounted in certain measurement scenario is the probe pattern compensation. It is well-know that the probe aperture introduces an averaging effect on the measured field which becomes important in case of electrically large probes and/or large AUT-probe view-angle [6-7]. For example, when electrically large objects are measured with wideband probes [8-9] it may become important to compensate for the effect of the probe pattern.

The fully probe corrected TSWE technique has been introduced in [10]. The proposed approach is based on a two-steps procedure where the TSWE is first applied to deal with the down-sampled dataset. Then, the full probe correction technique presented in [6-9] is applied to compensate for the probe effect. In [10] a first validation of the method was performed considering single frequency measured data of a standard gain horn.

In this paper the preliminary validation of the method is extended and consolidated considering measurements performed at several working frequencies of the same antenna.

As done in [10], the validation is carried out considering the measurement campaign reported in [6-7], where a standard gain horn (see Fig. 1) was mounted in an offset configuration and measured with a first order probe and two different wideband higher-order antennas as probe. To demonstrate the effectiveness of the proposed approach, only a subset of the SNF sampling points measured in that campaign is considered obtaining an almost two-times down-sampled dataset with respect to the conventional Nyquist criteria.

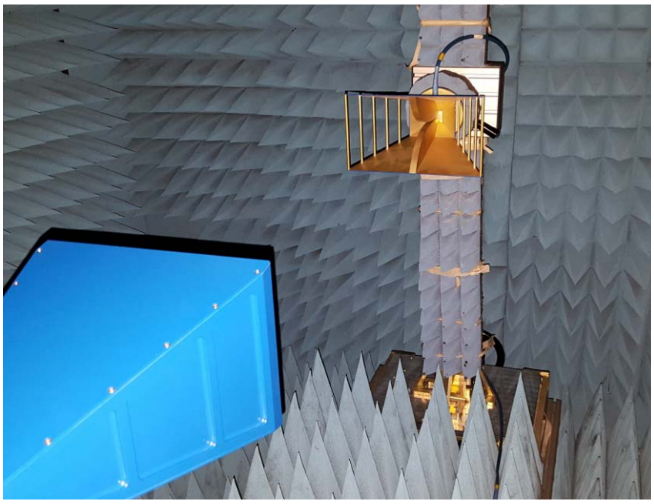

Fig. 1. MVG SGH820 during measurement with MVG SH800 dual-ridge horn used as a probe.

II. Fully Probe Compensated TSWE Technique

As anticipated in the introduction, the proposed Near-Field-to-Far-Field (NF/FF) transformation technique is a two-steps procedure where the TSWE and the full probe correction (PC) techniques both presented in previous publications [3-9] are combined. The two techniques are recalled in this section together with an explanation of the working procedure of the proposed approach.

A. Translated Spherical Wave Expansion (TSWE)

The TSWE is an advanced NF/FF transformation technique for SNF measurements with offset AUT. As demonstrated in [3-5], the advantage of using TSWE in case of offset AUT is the reduction of the number of NF measurement samples with respect to the conventional Nyquist criteria [1-2]. The TSWE algorithm is based on the definition of a new reference system (x', y', z') located on the AUT rather than on the center of the measurement sphere as shown in Fig. 2 This allows to define a smaller minimum sphere [1-2] $(R_{min,TSWE})$ with respect to the one that would be obtained considering the original coordinate system (x, y, z) located in the center of the measurement sphere, as done by conventional SWE. Using the TSWE, an offset AUT can thus be correctly represented with a minimum number of spherical modes reducing the number of measured NF samples (down-sampling). From Fig. 2 it is evident that a conventional 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 done in the conventional spherical NF/FF [2]. If the offset is along the z-axis the FFT can only be exploited for the φ-dependency while a matrix inversion must be involved for the θ-dependency. If the offset is along a generic x-y-z direction a more computationally demanding processing involving a full matrix inversion should be applied. In [5] an advanced version of TSWE (A-TSWE) which allows to reduce the complexity of the algorithm in this latter situation has been presented and validated experimentally.

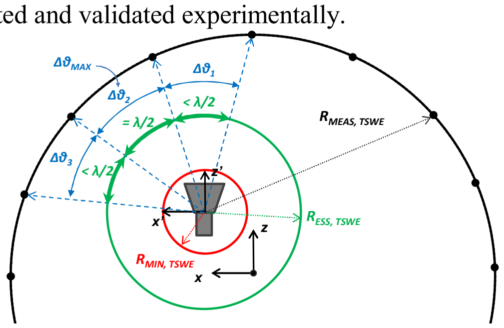

Fig. 2. Offset spherical NF measurement: coordinate systems and sampling criteria of the Translated-SWE.

In [4], guidelines for a correct equally-spaced sampling on the measurement sphere in case of NF/FF transformation performed with TSWE have been given. The minimum sampling which allows to have an Equivalent Sampling Sphere $(R_{ESS,TSWE})$ larger than the minimum sphere can be derived from equations (1) and (2),

$$\Delta\theta_{TSWE} \le \alpha \left(\frac{\pi}{k\, R_{min,TSWE} + n_{safety}}\right) \tag{1}$$

$$\alpha = \frac{\Delta\theta}{\Delta\theta_{MAX}} \approx \left(1 - \frac{|offset|}{R_{Meas}}\right) \le 1 \tag{2}$$

In such formulas k is the wavenumber and n_{safety} is an integer and positive number used as a safety factor [2]. The α-factor is purely geometrical, and it decreases, increasing the distance between the two reference systems $(offset)$ and reducing the measurement radius (R_{meas}).

B. Full Probe correction

The theory behind the full PC techniques has previously been presented in [6-9]. Such technique is also based on the SWE of the measured field [2]. The SWE is computed taking into account the so-called transmission formula [2] which is used to describe the measured field all over the scanning surface as a function of the AUT and probe Spherical Wave Coefficients (SWC). In order to take into account the entire spherical modal spectrum of the probe, each spherical wave function [2] is modified through the transmission formula, so that the probe spectral information is already included in the expansion basis. A linear system is then set-up and inverted using the modified spherical wave functions. In [6] it has been also pointed out that the solution of that linear system can be made efficient involving an FFT along the φ-axis.

C. TSWE as NF interpolator operator

The proposed two-steps NF/FF procedure makes use of the techniques recalled above as described in the following.

The measured NF is first expanded with the TSWE without considering the probe pattern effect. The computed SWC, which are now defined in the (x', y', z') reference system, are mathematically translated back [2] to the original coordinate system (x, y, z). The new set of SWC are thus used to recompute the spherical NF at the same measurement radius but increasing the number of sampling points. This first step is basically an interpolation of the measured field needed to retrieve a "virtual" SNF acquisition with full sampling. Once this is accomplished, the full probe correction is applied to the interpolated field as explained in the previous paragraph. Of course, if a first order probe [1-2] has been used in the measurement and/or the effect of the higher order probe can be neglected [11-12], the conventional First Order PC (FOPC) [2] can be applied instead of the full PC.

It should be noted that a similar goal could be obtained with the technique proposed in [13], where the probe effect is directly included in the expansion basis defined in the translated reference system. To account for the correct probe pointing and orientation, a different rotation operation must be performed at each measurement point increasing the complexity and the processing time of the computation. The proposed approach is instead more computationally efficient since no probe rotations are needed because the PC is performed in the original coordinate system, where the probe always points toward the center of the measuring sphere.

III. Validation Scenario

To experimentally validate the proposed approach, data already collected in the 9-12 GHz frequency range in the validation campaign of the full-probe correction technique [6] are considered. In such campaign hemispherical NF measurements were performed with a robotic arm system.

As shown in Fig. 1, the considered AUT is a standard gain horn working at X-Band (MVG SH820) having approx. 22 dBi of directivity. The aperture dimensions are 198x148 mm and the length is 353 mm. The AUT was mounted on the robotic arm so that, its mechanical interface corresponds to the center of rotation. Based on this displacement and on the AUT electrical dimension at the highest frequency, a sampling step of 1.5° along the θ-axis and of 5° along the φ-axis was chosen.

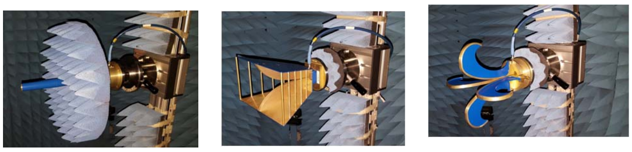

Fig. 3. MVG antenna used as probes; DOEW6000 first order probe (left); SH800 dual-ridge horn (center); QH800 open boundary quad-ridge horn (right).

As shown in Fig. 3, three MVG different antennas were used as probes for the validation: the DOEW6000 [14] first order probe which is used to perform reference measurements; the SH800 dual-ridge horn [15] and the QH800 open boundary quad-ridge horn [16]. These two horn antennas operate in the 0.8 - 12 GHz frequency range so they are very suited for wideband applications. Beside their wideband applicability, these types of antennas are also very mechanically stable and repeatable. As demonstrated in [7], these features allow the use of the probe pattern determined by full-wave simulation in the probe corrected NF/FF transformation without significant loss of accuracy, avoiding expensive and time-consuming probe calibration campaign. Furthermore, the QH800 is also a dual polarized device, making it even more appealing for usage as probe since it allows to measure simultaneously two orthogonal field components. The measurement probes were mounted on a tower in front of the robotic arm as shown in Fig. 1. The distance from the center of rotation and the probe aperture varies with the used probe and is approx. 1.1m.

The azimuthal spherical wave spectrum (m-modes) [2] versus frequency of the SH800 is shown in Fig. 4. As can be seen such antenna is characterized by many higher order modes (up to |m|=23 considering a threshold level of -40 dB) whose effect must be compensated with the full PC technique. It is observed that the SH800 only radiates odd higher order modes which make the radiation pattern cuts symmetric with respect to the boresight [10].

The azimuthal spherical wave spectrum of the QH800 is instead shown in Fig. 5 and Fig. 6 respectively for the odd and even higher order modes. The even-order modes introduce asymmetries in the radiation pattern cuts [10], making the measurements with such antenna as probe even more challenging.

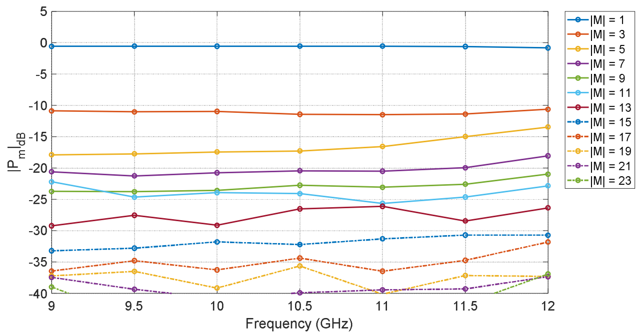

Fig. 4. Azimuthal modal content of the SH800 versus frequency.

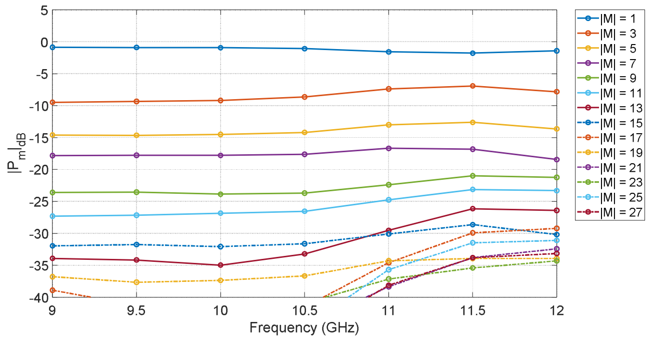

Fig. 5. Azimuthal modal content of the QH800 versus frequency (odd modes).

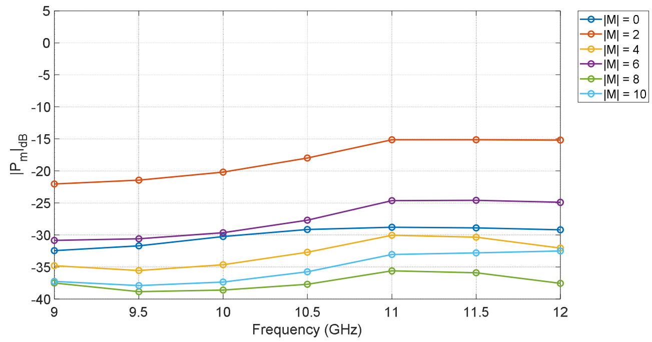

Fig. 6. Azimuthal modal content of the QH800 versus frequency (even modes).

The outcomes of such validation are summarized in Fig. 7 and Fig. 8 where the H-plane directivity pattern comparisons at 10 GHz and 12 GHz are respectively reported. The patterns obtained by measuring the AUT with the three different probes are shown from both the co-polar (solid traces) and cx-polar (dotted traces) field components. The blue traces are relative to the measurement with the DOEW6000 and NF/FF transformation with FOPC; the orange and yellow ones are instead relative to the measurements with the SH800 and QH800 respectively and processed with the full PC. It is observed that full-wave simulated [17] probe pattern are considered in the application of any type of PC. As can be seen the agreement among the co-polar patterns is excellent. The cx-polar performances are also very good with only small differences due to minor uncertainties in the probe manufacturing which slightly affect the probe cx-polar and that are not accounted in the full-wave simulation of the probe [7].

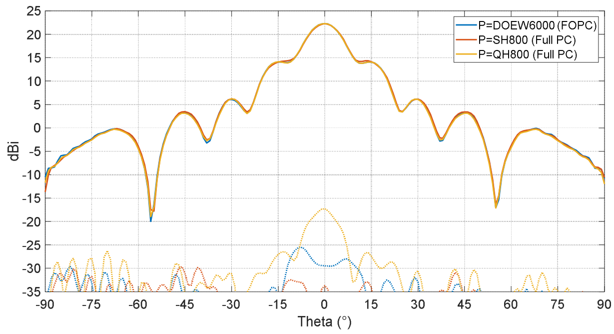

Fig. 7. Directivity H-plane pattern comparison of the SGH820 @ 10 GHz measured with full sampling using different probes.

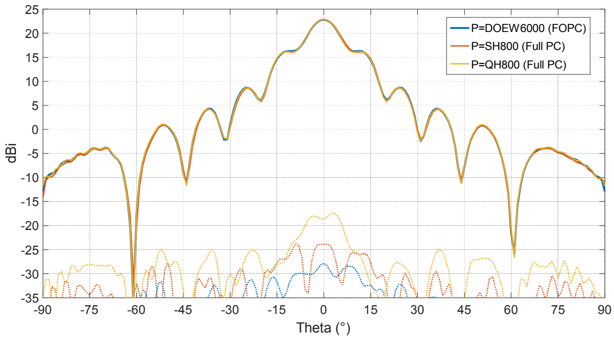

Fig. 8. Directivity H-plane pattern comparison of the SGH820 @ 12 GHz measured with full sampling using different probes.

IV. VALIDATION RESULTS

To validate the proposed approach, SNF data from the measurement campaign recalled in previous section have been decimated with a factor of two along the θ-axis, so that the modified dataset exhibits a 3° sampling step along the θ-axis. The 5° sampling rate have instead been kept along the φ-axis.

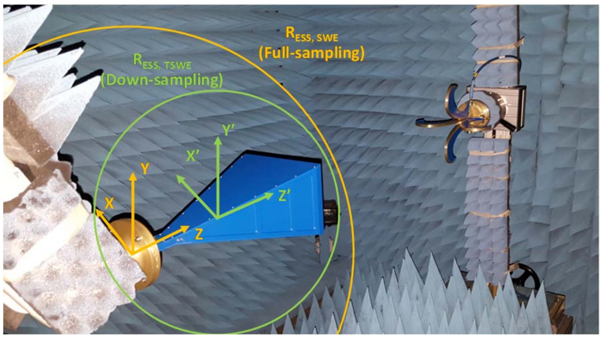

Fig. 9. Illustration of the coordinate systems and the Equivalent Sampling Spheres (ESS).

At the higher frequency (12 GHz), the minimum θ-sampling rate according to the Nyquist criteria when the reference system is in the center of the measurement sphere is approx. $\Delta\theta = 1.7°$. The θ-sampling considered in the performed measurements is $\Delta\theta = 1.5°$. The radius of the obtained Equivalent Sampling Sphere (ESS) is approx. 48 cm and is more than enough to fully include the AUT (see orange ESS in Fig. 9). The $\Delta\theta = 3°$ sampling rate considered in this validation is not sufficient to measure the AUT if the standard SWE is used. In fact, in such case, an ESS centered in the (x, y, z) reference system with approx. only 24 cm radius would been obtained. By using the TSWE, the new (x', y', z') expansion origin shown in Fig. 9 has been defined. Such new reference system is translated of $z = +18cm$ with respect to (x, y, z) and is roughly located in the geometrical center of the AUT. The corresponding ESS is illustrated by the green circle shown in Fig. 9. The radius of this ESS, obtained with formula (1)-(2), is approx. 20 cm and is sufficient to fully include the considered AUT.

The accuracy of the performed tests is evaluated in term the Equivalent Noise Level (ENL) defined by equation (3) where, $E(\theta, \varphi)$ is the reference pattern and $\tilde{E}(\theta, \varphi)$ is the test pattern.

$$ENL = 20\log_{10}\left(RMSE\left|\frac{E(\theta,\varphi) - \tilde{E}(\theta,\varphi)}{E(\theta,\varphi)_{MAX}}\right|\right) \quad (3)$$

The ENL is evaluated considering as reference the directivity pattern obtained applying the NF/FF with FOPC to the measurement performed with the DOEW6000 as probe with full sampling. The metric has been evaluated for each measured frequency on the full hemispherical 3D-pattern (considering the total field).

The ENLs obtained in case of decimated (down-sampled) measurements with the DOEW6000 probe are shown in Fig. 10. The black dashed trace is relative to the NF/FF transformation with conventional SWE without PC. As expect in this case the error is quite high because with the conventional SWE is not possible to define an ESS that include the AUT. The orange and green traces are instead relative to the NF/FF using TSWE respectively without and with probe correction. As can be seen in these cases the errors are much lower. It is observed that a very good accuracy is achieved both with and without PC, meaning that in some cases (e.g. electrically small / low directive probes) the effect of the probe can be neglected during the NF/FF transformation.

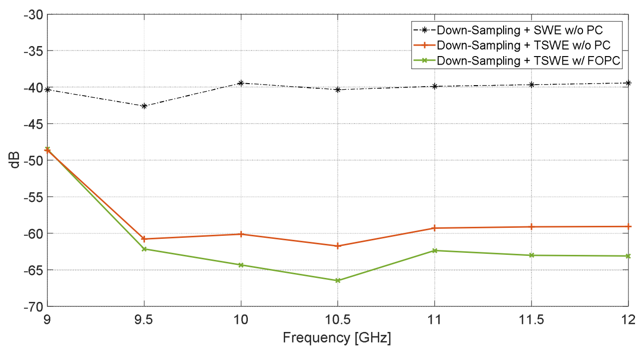

Fig. 10. ENL comparison with frequency for the measurements with the DOEW6000 first order probe.

The ENLs obtained by processing the measurements performed with the SH800 as probe are reported in Fig. 11. The blue trace is relative to the processing of the full-sampled measurement with full PC and is in very good agreement with the reference. The error obtained by processing the down-sampled dataset (black dashed trace) with the conventional SWE is as expected relatively high. Instead, if the down-sampled measurement is NF/FF transformed with TSWE without PC (orange trace), the improvement of the ENL is between 4 and 10 dB, depending on the frequency. If the full PC is also applied (green trace) a further improvement is obtained, reaching the same error level of the full-sampled measurement.

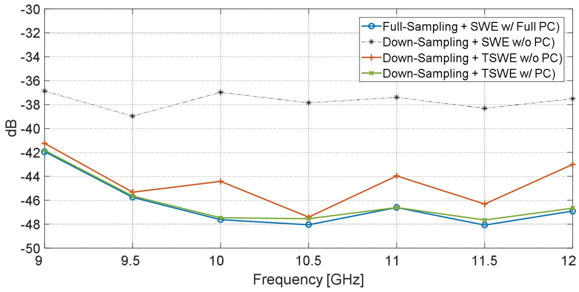

Fig. 11. ENL comparison with frequency for the measurements with the SH800 as probe.

A similar comparison to the one shown in Fig. 11 is reported in Fig. 12 for the measurements performed with the QH800 as probe. Due the complexity of the considered probe, in this case the deviation of the TSWE-transformed data without PC from the one with full PC is higher, remarking the need of applying the compensation of the probe pattern.

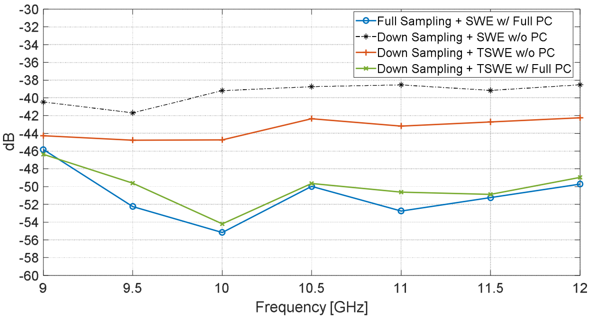

Fig. 12. ENL comparison with frequency for the measurements with the QH800 as probe.

V. Conclusions

SNF measurements of an offset X-band standard gain horn performed with three antennas of different complexity as probe have been considered to experimentally validate the fully probe compensated Translated Spherical Wave Expansion (TSWE) technique at several frequencies. The measurements, originally performed with full sampling, have been decimated obtaining an almost 2-time down-sampled dataset wrt the Nyquist criteria.

The TSWE applied with and without probe compensation (PC) to the measurement performed with a first order probe of 10 dBi directivity shows, as expected, that in some measurement scenarios accurate results are obtainable even without any PC.

In measurements scenarios with probes of higher-order with very large bandwidth (15:1), which are thus well suited for modern multi-services antenna systems [8-9], the PC is clearly needed. In such cases it has been shown that the effect introduced by the more complex probe pattern and higher order probe spherical modes can be fully compensated even in case of down-sampling considering the proposed technique.

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