Spherical Near Field Measurements of Electrically Large Offset Antennas with Minimum Sampling

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***Abstract*—The translated spherical wave expansion is an advanced near field to far field transformation technique which allows to efficiently deal with spherical near field measurement of offset mounted antennas. While in the past this technique has been extensively validated considering low/medium directive antennas mounted on complex structures like vehicles, it hasn't yet been applied to electrically large antennas. In this paper, spherical near field measurements of a 30dBi reflector antenna measured in different offset configurations will be presented. The effectiveness of the translated wave expansion will be validated considering up to more than 4-time down-sampling with respect to the conventional requirements.**

***Index Terms*—spherical wave expansion, downsampling, spherical near field, offset, translation.**

I. Introduction

Spherical Near Field (SNF) measurements are one of the most accurate techniques for the characterization of the antenna radiating performance [1]-[2]. From the near field sampled on a spherical surface with a constant angular step, the Spherical Wave Expansion (SWE) is typically applied to perform the Near-Field to Far-Field (NF/FF) transformation. It is well known that the sampling requirement depends on the electrical size of the minimum sphere, centered in the origin of the coordinate system, fully enclosing the Antenna/Device Under Test (AUT/DUT) [2]. Electrically large and/or offset antennas could lead to high spatial sampling densities and consequently to prohibitive measurement time.

In case of offset radiating devices, the Translated-TSWE (TSWE) can be used to significantly reduce the required number of samples and hence the measurement time [3]. The TSWE is based on the definition of a new reference system located on the antenna rather than on the centre of the measurement sphere as done in the conventional SWE. The definition of the local reference system allows the reduction of the size of the minimum sphere and the consequent optimization of the required measurement samples. The downside of the TSWE is an increase of the complexity of the expansion process because the NF samples in the translated coordinate system are not anymore equally spaced. Therefore, for arbitrary xyz-offset of the antenna, the two-dimensional Fast Fourier Transform (FFT) cannot be applied as done in the conventional SWE.

The TSWE was first introduced and validated in [3] considering a medium directive horn antenna offset along the z-axis. This may occur in case of mechanical constraints of the measurement system, such as the mast or stand-offs of fixed length, used to handle the DUT.

In the field of automotive antenna measurements, where low/medium directive antennas are arbitrarily mounted on the vehicles, the TSWE has recently found a considerable use [4]-[8]. Standard size cars (e.g. 5m) with antennas working at frequencies like 6GHz would require near field sampling steps in the order of 0.5° for both scanning axis, which can be a limiting factor for some type of measurement systems, or simply could lead long acquisition time. The TSWE can in such cases be combined with the so-called local measurement approach, assuming that only a relatively small portion of the structure around the antenna (e.g. 15/20λ) would significantly contribute the final radiation [4].

A further application of the TSWE comes again from the vehicle antennas measurement and is about the enforcement of the PEC boundary conditions when conductive floors are located at arbitrary height [9]-[11].

The application of the TSWE to high directive antennas has yet never been reported. Due to the electrical size, directive antennas require a significant sampling density also when mounted in onset configuration. When such types of antennas are offset-mounted on complex structures such as satellites, the sampling requirements are further increased unless the TSWE technique is adopted. It should be noted that in such a case the local measurement approach is expected to be even more effective than in the case of electrically small antennas because of the lower interaction with the surrounding structure.

Fig. 1. MVG SR40-A offset reflector antenna fed by a closed boundary quad-ridge horn (QR18000).

In this paper a step forward in the validation of the TSWE technique will be presented. In particular, the TSWE will be applied for the first time to an electrically large antenna with more than 30dBi of directivity. The considered antenna is the SR40-A offset reflector fed by a closed boundary quad-ridge horn (QR18000) shown in Fig. 1. The electrical size of the SR40A at 18GHz is approximately 24λx34λx19λ and the maximum considered offset in the validation is about 60λ, giving rise to a global minimum sphere of 83λ radius and a minimum sampling step in the order of 0.3° with conventional SWE technique. In this contribution it will be shown that accurate pattern measurements can be achieved considering up to 4-time down-sampling in this case.

II. TRANSLATED-SWE

The Translated-SWE is based on the definition of a local coordinate system (x', y', z') placed on the AUT [3]-[4] as shown in Fig. 2. The choice of an optimal reference system allows to keep the size of the minimum AUT sphere to the minimum, reducing the sampling requirements because less spherical wave modes are needed to represent the AUT field.

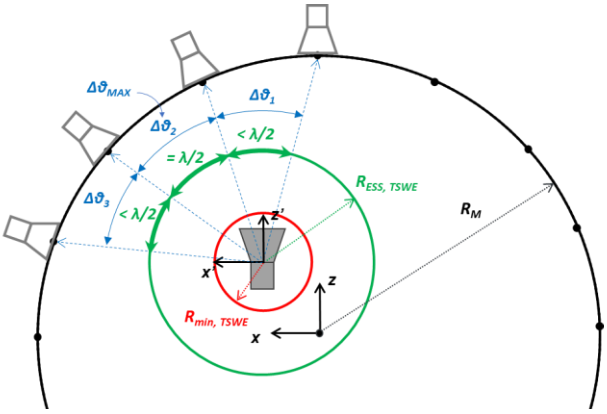

Fig. 2. Illustration of the Translated-SWE concept: definition on the local cordinate system on the antenna and sampling implications.

From Fig. 2 it is evident that with the local reference system an offset measurement sphere is obtained which complicates the relative distribution of the NF samples which are at different distances from the new origin and are not equally spaced anymore. This has a direct impact on the processing which cannot exploit the FFT, and has to resort to a generalized matrix-inversion-based expansion. This increase of the complexity of the expansion can be significantly reduced when the local reference system is translated only along the z-direction. In fact, in this case the constant spacing of the samples along the ϕ-axis is kept and a hybrid FFT / matrix inversion approach can be adopted [12]. Instead, when a generic xyz-translation is considered, the regular spacing of the sampling is lost both along the θ- and ϕ-axis hence, a full matrix inversion should theoretically be applied as done in [4]. To overcome this limitation, an approximate solution of the TSWE has been proposed in [5]. With such approach, pre-translation and rotation operations are applied on the measured NF to align the z-axis with the direction of the offset creating a "virtual" scenario where the FFT can still be applied along the newly defined ϕ-axis.

The non-uniformity of the measured samples in the local coordinate system has some implications on the resulting Equivalent Sampling Sphere (ESS) and on the sampling requirements. The ESS is defined as the sphere that realizes the equivalent half-wavelength sampling. In the original coordinate system, the radius of the ESS is $R_{ESS,SWE} = \lambda/(2\,\Delta\theta)$, with $\Delta\theta$ being the constant angular sampling step. In the local coordinate system, the ESS is defined considering the maximum angular step $(\Delta\theta_{MAX})$ so that the half-wavelength equivalent sampling is unsured everywhere in the ESS. In particular the radius of the ESS $(R_{ESS,TSWE})$ obtained with the TSWE is given by (1) and (2)

$$R_{ESS,TSWE} = \frac{\lambda}{2\,\Delta\theta_{MAX}} = \alpha R_{ESS,SWE} \tag{1}$$

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

The α-factor defined in (2) is purely geometric and depends on the offset (i.e. Euclidian distance between original and local coordinates) and the measurement radius R_M.

The minimum sampling requirements when the TSWE is applied are reported in (3), where $R_{min,TSWE}$ is the radius of the AUT minimum sphere (in the local coordinate system) and n_{safety} is the conventional safety factor used ensure a proper convergence of the expansion [13].

$$\Delta\theta_{TSWE} \leq \alpha \left(\frac{\pi}{k\,R_{min,TSWE} + n_{safety}}\right) \tag{3}$$

III. MEASUREMENTS DESCRIPTION

The AUT selected for this investigation is the SR40-A offset reflector antenna fed by a closed boundary quad-ridge horn (QR18000) shown in Fig. 1. The considered test frequency is 18GHz. The rim of the reflector is 40x40cm and its F/D is 0.5. Such antenna fits on a minimum sphere of 0.75m diameter (~45λ) and has maximum directivity of 31dBi at 18GHz.

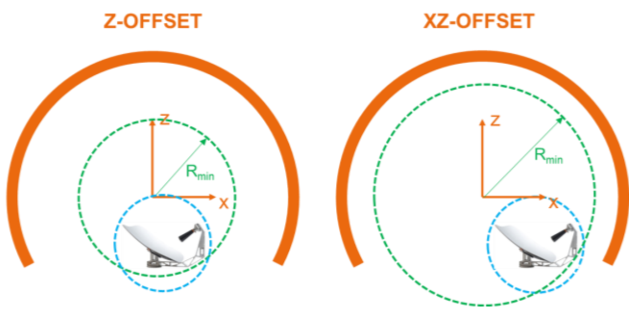

Fig. 3. Schematic illustration of the SR40-A fed by QR18000 measured in different offset conditions.

As depicted in Fig. 3 the AUT has been measured in a spherical multi-probe system with two different displacements: one along the z-axis (vertical) and one along both the x- and z-axis (horizontal and vertical). The exact offset positions along with the resulting minimum sphere information (see green spheres in Fig. 3) are reported in TABLE I. The measurement distance (R_M) of the considered multi-probe system is 4.2m, giving rise to α-factors of 0.88 and 0.76, respectively for the two AUT displacements. The minimum sampling required by the conventional SWE and TSWE approaches are also reported TABLE I. for both scanning axes ($\Delta\theta$ and $\Delta\phi$).

The sampling density considered in the actual measurements of the AUT is higher than the minimum one, allowing the generation of accurate, aliasing-free, reference data using the conventional SWE technique. To test the capabilities of the TSWE, the acquired SNF data have been spatially decimated, generating down-sampled dataset. The considered Down-Sampling Factor (DSF), defined as the ratio between the sphere points of the minimum SWE-based sampling and the sphere points of the decimated dataset, is 1.9 for the z-offset configuration. This approximately correspond to the minimum sampling required by the TSWE. For the xz-offset configuration, two DSFs are considered, namely 1.8 and 4.2. The latter approximately correspond to the minimum TSWE sampling.

TABLE I. DETAILS OF THE TEST CASE SCENARIOS

	Z-offset case	**XZ-offset case**
Antenna XYZ offset [m]	(0, 0, -0.483)	(0.866, 0, -0.483)
R_{min} [m]	0.98	1.49
α	0.88	0.76
Min. Sampling (SWE)	Δθ=0.47°, Δϕ=1.09°	Δθ=0.31°, Δϕ=0.37°
Min. Sampling (TSWE)	Δθ=0.81°, Δϕ=1.09°	Δθ=0.70°, Δϕ=0.86°
Measurement Sampling	Δθ=0.41°, Δϕ=0.49°	Δθ=0.23°, Δϕ=0.23°
Test Sampling (decimation)	Δθ=0.83°, Δϕ=0.98° (DSF=1.9)	Δθ=0.46°, Δϕ=0.46° (DSF=1.8) Δθ=0.69°,Δϕ=0.69° (DSF=4.2)

IV. MEASUREMENT RESULTS

Results in terms of directivity radiation patterns are reported in this section. For the different configurations the pattern cut intersecting the offset plane of the reflector is reported for the measurement with the full sampling (blue traces, considered as reference) and the down-sampled dataset processed with the SWE (black traces) and the TSWE (orange traces). The Equivalent Noise Levels (ENL) defined by the following expression,

$$ENL(\theta, \varphi) = 20\log_{10}\left(\left|\frac{E(\theta, \varphi) - \tilde{E}(\theta, \varphi)}{E(\theta, \varphi)_{MAX}}\right|\right) \quad (4)$$

where $E(\theta, \varphi)$ and $\tilde{E}(\theta, \varphi)$ are respectively the reference and test directivity pattern are also reported (dashed traces).

Directivity pattern results for the z-offset configuration are reported in Fig. 4. Despite the down-sampling, the conventional SWE technique is capable to accurately reconstruct the main beam and the first sidelobes. This is due to the fact that most of the radiating part of the reflector is included in the ESS of such down-sampling dataset resulting in a fairly good reconstruction. Nevertheless, part of the antenna (i.e. part of the feed and its arm) is left outside the ESS, resulting in a degradation of the accuracy of the sidelobes at approx. θ>15°. On the other hand, the TSWE allows a better centering of the ESS around the antenna with a consequent reduction of the measurement errors.

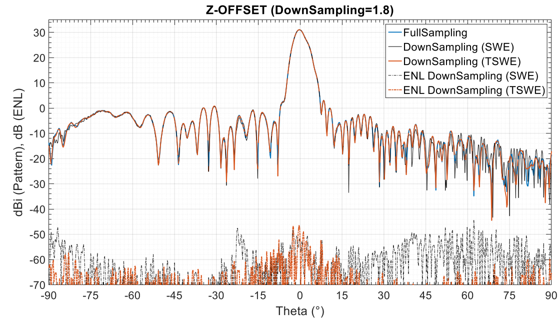

Fig. 4. AUT measured in z-offset configuration with DSF=1.9: comparison of directivity radiation patterns (solid) and ENL (dashed).

In Fig. 5 the pattern results obtained with the xz-offset configuration considering a DSF=1.8 are reported. In this case a significant degradation is observed on the main beam if the SWE technique is applied, with an ENL reaching a maximum value of approx. -24dB. Applying the TSWE instead, the worst case ENL is lower than -45dB.

Results of the same xz-offset scenario but with the significantly higher down-sampling (DSF=4.2) are shown in Fig. 6. The application of the conventional SWE to this scenario, dramatically corrupts the pattern reconstruction. In fact, its main beam is more than 20° titled and its directivity is more than 5dB lower than the reference one. On the other hand, the TSWE allowed to achieve an accurate pattern reconstruction with a worst case of ENL of approx. -43dB.

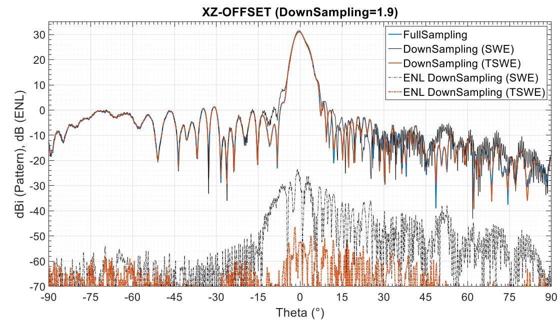

Fig. 5. AUT measured in xz-offset configuration with DSF=1.8: comparison of directivity radiation patterns (solid) and ENL (dashed).

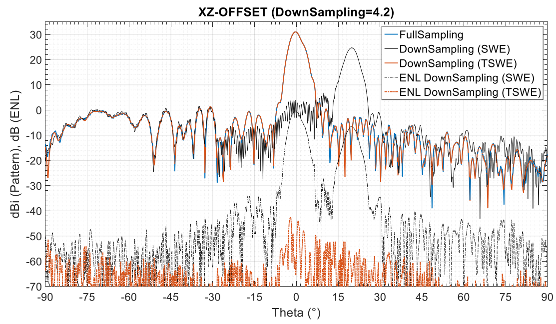

Fig. 6. AUT measured in xz-offset configuration with DSF=4.2: comparison of directivity radiation patterns (solid) and ENL (dashed).

To better understand the physics behind the achieved results, the spherical wave spectra (represented by the P_n power spectra curves [13]) of the xz-offset scenarios are reported in Fig. 7. The blue trace is the reference obtained from the fully sampled acquisition and the SWE processing. Due to the offset and the resulting minimum sphere centered at origin of the system (R_{min}=1.49m), more than n=500 modes are needed to make the SWE converge. The SWE of the measurement with DSF=1.8 (orange dashed trace) does not allow a proper convergence of the expansion, giving rise to the errors observed in Fig. 5. Instead, with the TSWE the reference system is moved to the AUT achieving a good convergence (solid red trace) and a good pattern reconstruction. Finally, when the DSF is increased to 4.2, not even the peak of the spectrum can correctly be computed with the SWE (green dashed trace), consequently the achieved reconstructed pattern is dominated by the aliasing errors. Again, with the TSWE the reference system is moved to the AUT allowing to concentrate all the radiating contributions in the n=200 available spherical modes (green solid traces).

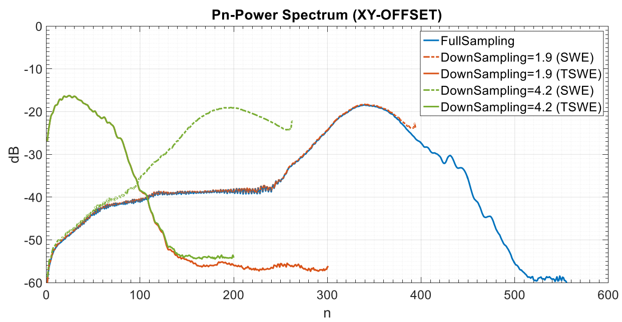

Fig. 7. DUT measured in XZ-offset configuration: comparison of Pn power spectra obtained with different down-sampling and data processing.

The global ENL, obtained combining with the Root Mean Square (RMS) the ENL in any $\theta\phi$ direction (i.e. whole 3D pattern), is reported in TABLE II. for each measurement scenario and both the SWE and TSWE data processing. The improvements achieved with TSWE are evident. The achieved global ENLs are all below the -60dB threshold, corresponding to a 1σ-uncertainty of <0.01dB at the peak of the pattern, <0.1dB at -20dB signal level and <0.3dB at -30dB.

TABLE II. GLOBAL ENL COMPUTED FROM THE WHOLE 3D PATTERNS

	ENL SWE [dB]	**ENL TSWE [dB]**
Z-offset (DSF=1.9)	-59.9	-63.7
XZ-offset (DSF=1.8)	-38.8	-62.8
XZ-offset (DSF=4.2)	-15.4	-60.5

V. CONCLUSIONS

The Translated Spherical Wave Expansion (TSWE) allows to efficiently deal with SNF measurements of off-centered test antennas. While the TSWE technique has been extensively validated in the past considering electrically small antennas mounted on complex structures like vehicles, in this paper it has been applied to offset measurements of a high directive reflector of approximately 30dBi. A worst-case scenario with an offset of approx. 60λ along the xz-axes and a down-sampling factor of 4.2 with respect to the conventional sampling requirements has been considered. The achieved excellent pattern results suggests that the use of TSWE can indeed be extended to electrically large antennas.

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