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Antenna Gain Determination in the Near-Field Using Propagating Plane-Wave Expansions

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Abstract

A propagating plane-wave based transmission equation is presented for measuring the far-field gain and radiation pattern of an antenna in the near-field. In contrast to many Fast Fourier Transform accelerated methods, the transformation algorithm is capable of working with incomplete and irregularly shaped measurement surfaces. This is demonstrated by using numerical results obtained from near-field measurement data.

1 Introduction

To determine the gain of an antenna under test (AUT) from measurements in the near-field it is common to employ so called "direct methods" in order to avoid repeated measurements [1]. In these cases, the gain of the probe antenna has to be known and the near-field transmission equation is evaluated directly. This was first shown for planar measurements, where the radiated field of the AUT is expanded in plane waves on a reference plane [2]. For spherical scans an expansion in spherical modes is common [3]. Both approaches typically rely on a Fourier transform of the measurement data to determine the far-field pattern. As this is usually done by means of the Fast Fourier Transform (FFT), only canonical measurement surfaces can be processed. Especially for planar scans, the measurement surface is often required to be sufficiently large, so that the electric field can be assumed to be almost zero outside. More flexible measurement scenarios are possible with an expansion of the electric fields in propagating plane waves on the Ewald sphere [4]. In this contribution a near-field transmission equation based on such an expansion is presented, which allows to determine the realized gain pattern of the AUT. This is demonstrated using irregular near-field measurement data that does not conform to the aforementioned requirements for FFT based methods. In particular, it is observed that only a small part of the radiated near-field has to be captured to accurately determine the maximum gain of the antenna.

2 Near-field far-field transformation

Using a propagating plane-wave expansion of the free space Green's function $\overline{\mathbf{G}}_J^E$ as it is described, e. g., in [5], the electric field radiated by the AUT and incident on a probe antenna, both separated by a distance D between their phase reference points, may be written as

$$\boldsymbol{E}(\boldsymbol{r}) = \lim_{L\to\infty} \oiint T_L\left(\hat{k}\cdot\hat{D}, kD\right) \tilde{\boldsymbol{V}}_{AUT}(\boldsymbol{k})\, \mathrm{d}^2\hat{k}, \qquad (1)$$

where $\tilde{\boldsymbol{V}}_{AUT}(\boldsymbol{k})$ is the radiated plane-wave spectrum of the AUT, $\boldsymbol{k}$ are the wave vectors of the plane waves and $T_L\left(\hat{k}\cdot\hat{D}, kD\right)$ is the translation operator, known from the fast multipole method (FMM). By invoking the equivalence theorem together with the reciprocity theorem [6], the receive voltage U_R at the probe antenna port at $\boldsymbol{r}_m$ can be derived from

$$-U_R(\boldsymbol{r}_m)\, I_R = \iiint_{V_p} \boldsymbol{J}_R(\boldsymbol{r}-\boldsymbol{r}_m)\cdot\boldsymbol{E}(\boldsymbol{r})\, \mathrm{d}v, \qquad (2)$$

where I_R is the probe feeding current in transmit mode, $\boldsymbol{J}_R$ is an equivalent source current density of the probe and we integrate over the probe volume V_p [4]. Using the realized gain patterns $\boldsymbol{W}_T(\boldsymbol{k})$ and $\boldsymbol{W}_R(\boldsymbol{k})$ of AUT and probe, respectively, it may be shown that the complete near-field transmission between the antenna ports becomes

$$s_{21} = \lim_{L\to\infty} \oiint \frac{1}{\mathrm{j}2k} \boldsymbol{W}_R(-\boldsymbol{k})\cdot T_L\left(\hat{k}\cdot\hat{D}, kD\right) \boldsymbol{W}_T(\boldsymbol{k})\, \mathrm{d}^2\hat{k}. \qquad (3)$$

Noting that $|W_{T/R}| = (G_{T/R})^{1/2}$ with the realized gain $G_{T/R}$ and using a far-field approximation for T_L as described in [7], equation (3) reduces to the well known Friis transmission equation in the asymptotic case of large distances D. Although we work with the realized gain of the antennas, the IEEE gain may similarly be obtained by additionally considering a mismatch factor.

Equation (3) may be solved for the unknown realized gain pattern of the AUT by choosing an appropriate source representation and performing the k-space integration numerically. While there is generally no constraint on the location of the measurement samples s_{21}, only a completely closed surface around the AUT with a maximum spacing of a half wavelength between the samples with respect to the minimum sphere of the AUT guarantees an exact reconstruction of the complete radiation pattern. However, to accurately determine the maximum gain of the antenna in main beam direction, only relatively few near-field samples in the area of the main lobe are sufficient, which will be shown in the next section. We solve the linear equation system iteratively using the generalized minimal residual solver (GMRES) [8].

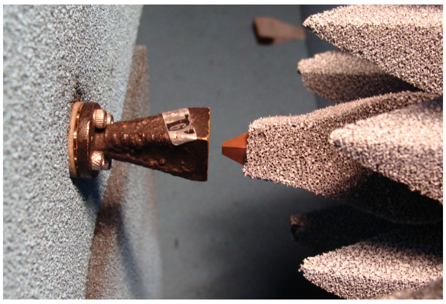

Figure 1. Standard gain horn antenna in the millimeter-wave near-field scanner of TUM.

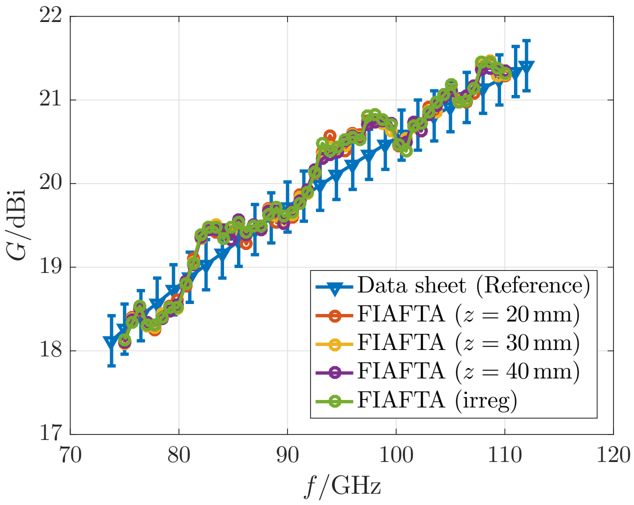

Figure 2. Comparison of gain values of standard gain horn in W-band.

3 Numerical Results

To demonstrate the capabilities of the presented transformation algorithm, a standard gain horn antenna (SGH272740) [9] in the W-band was measured in the millimeter-wave near-field scanner of the Technical University of Munich (TUM) as shown in Fig. 1. Using an open-ended waveguide probe, planar scans for three different aperture-to-aperture distances of 20 mm, 30 mm and 40 mm were conducted. To additionally test the performance of the transformation algorithm in case of irregularly distributed measurement locations, randomly chosen samples from the three measurements were combined to yield a new scenario with varying distance. For all measurements the transformation needs around 35 solver iterations to reach a relative residual error of 10^{-4} and a relative near-field error of about $2 - 4\,\%$. As can be seen from Fig. 2, the computed realized gain values in boresight direction of the AUT agree well to each other and to the data sheet reference values, which are given with an accuracy of ± 0.3 dB. The xy-measurement-planes of the scans cover a range of $x_{max} = \pm 250$ mm and $y_{max} = \pm 130$ mm. To assess the minimum range required to accurately determine the boresight gain of the AUT, the size of the measurement planes is gradually decreased in the x- and y-direction and the absolute error of the maximum

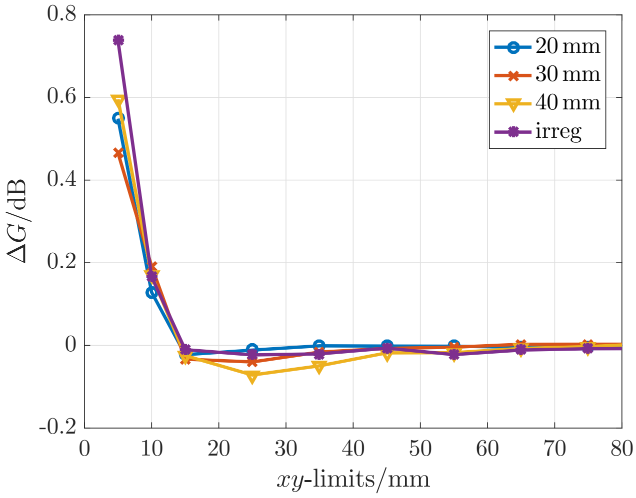

Figure 3. Maximum gain error for reduced measurement plane.

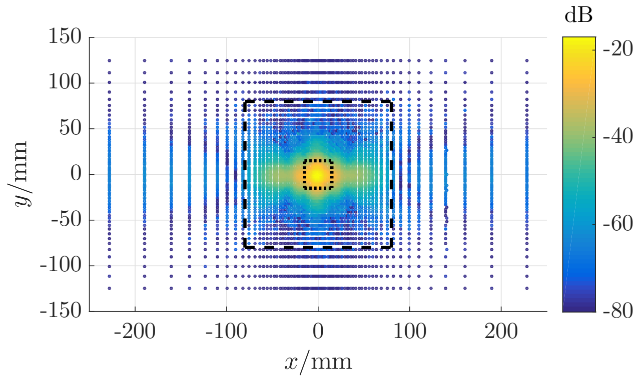

Figure 4. Magnitudes of near-field samples from non-redundant planar measurement of standard gain horn. Dotted line: Limitation to ± 15 mm in x- and y-direction. Dashed line: Limitation to ± 80 mm in x- and y-direction.

gain ΔG with respect to the full-plane solution is calculated. As shown in Fig. 3, the measurement plane can be limited down to ± 15 mm without introducing an error $\Delta G > 0.1$ dB. Obviously, this corresponds to a significant reduction of the number of measurement samples as can be seen from Fig. 4, showing the normalized amplitudes of one polarization for the planar scan at $z = 40$ mm. For all planar scans a non-redundant measurement scheme as described in [10] was used. The dashed and dotted line indicate a limitation of the measurement plane to ± 80 mm and ± 15 mm, respectively. It is also noted that at ± 15 mm the near-field magnitude has only dropped by -10 dB compared to the main lobe, which is in contrast to FFT based methods where typically around -60 dB are required.

4 Conclusion

By expanding the radiated near-field of an antenna in propagating plane waves, a near-field transmission equation can be derived that allows to determine the realized gain pattern of the antenna from irregularly distributed measurement samples. W-band measurement data was used to validate the formulation and it could be shown that relatively few near-field samples are sufficient to determine the maximum gain.

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