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Suppression of Reflections by Directive Probes in Spherical Near-Field Measurements

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Abstract—The influence of probe correction in spherical near-field measurements on signals from outside the test volume is investigated theoretically and experimentally. It is found that the suppression of reflections obtained by a directive probe is not disturbed by the probe correction. A geometric relation between the antenna "minimum sphere" and the probe pattern beamwidth is established, whose satisfaction guarantees the absence of numerical instabilities in the far-field computation. The condition is sufficient, but not necessary if the "minimum sphere" of the antenna is in the near field of the probe.

I. INTRODUCTION

In the spherical near-field far-field technique [1]-[4], the near field is measured on a sphere surrounding the test antenna. Then the far field can be computed in all directions and the directivity can be determined. Often a directive antenna is used as probe, which leads to an amplitude taper over the test aperture so that the field contributions from the outermost parts of the test antenna are attenuated. The probe correction, being a part of the near-field far-field transformation, makes a correction for this effect. Another way of describing the correction is to say that it corrects for the probe measuring a weighted average over the probe aperture rather than the value at a single point.

Probe correction is also applied in planar near-field measurements [5]. Here, the correction can be regarded as a division of the Fourier-transformed measured data by the radiation pattern of the probe. Hence, the correction tends to amplify the test antenna pattern in directions away from boresight. In the presence of error signals and noise this can lead to large errors in the null directions of the probe.

In the spherical technique there is no similar simple interpretation of the probe correction. Since the signals from current elements away from the center of the test volume are attenuated by the probe pattern, these signals must be amplified by the probe correction. For instance the sidelobes of a reflector antenna are raised by the correction [6]. One could think that spurious signals from the surroundings outside the test volume could also be amplified as in the planar technique. The question of how the probe correction treats these error signals is the subject of a M.Sc. thesis [7] and the present paper.

II. EXPERIMENTAL STUDY OF REFLECTIONS

In the experimental part of our investigation we have performed a series of measurements at 11.7 GHz with the spherical scanner in the radio anechoic chamber at the Technical University of Denmark. The near field of a 30 λ reflector antenna was measured and transformed to the far field by use of the program SNIFTC [8]. In order to study the influence of probe directivity two probes were used: a 15 dB gain conical horn and an open-ended circular waveguide with a gain of approximately 5 dB. Corrections for the probe patterns were included in the transformations.

The spherical scanner geometry is shown in Fig. 1. The probe is fixed while the test antenna is rotated in θ and φ. We inserted a 1 m × 2 m aluminum plate into the anechoic chamber with the middle of the plate at the same height as the probe and test antenna, so that a large reflected error field was produced.

In the near field (not shown here), the directive probe obviously gives the best suppression of the reflected error signal; but it is not obvious that this also applies to the transformed and probe-corrected far field. Fig. 2(a) shows the far field without reflections, while Figs. 2(b) and 2(c) show the far fields when the large reflection is introduced, giving rise to a large lobe at θ = 50°. The directive probe pattern is 13 dB below the pattern of the waveguide probe in the direction of specular reflection, and by comparing Figs. 2(b) and 2(c) we see that this suppression of the reflection in the near field is maintained in the far field. The probe correction amplifies the lobes generated by currents inside the test antenna volume and away from center [9], but it does not amplify the error signals. Thus the directive probe yields the best suppression of the reflections.

A series of computer simulations of different measurement situations has been carried out, and the simulations confirm the experimental results [7].

III. THEORETICAL COMPARISON OF PROBE CORRECTIONS

In the planar technique the probe correction mechanism is normally described as a "division" of the measured and Fourier-transformed data by the radiation pattern of the probe. Although the cylindrical and spherical probe corrections are not as simple as this, we have established an analogy between the probe corrections in the three techniques.

First, let us give a brief summary of the planar technique as described by Kerns [5]. Introducing the transverse displacement of the probe \( P = xe_x + ye_y \), the received signal in the probe is

\[
b'_0(P) = a_0 \int e^{iK'P} S_{02}(K) \cdot S_{10}(K) e^{i \gamma d} dK
\]

where \( K = k_x e_x + k_y e_y \) is the index parameter for the plane wave expansion, \( S_{02}(K) \) is the receiving characteristic of the probe, and \( S_{10}(K) \) is the wanted transmitting characteristic of the test antenna. Both of these are two-component vectors, and for each \( K \), the two components correspond to two orthogonal polarizations. Equation (1) represents a Fourier transformation, and by inversion we obtain

\[
S_{02}(K) \cdot S_{10}(K) = \frac{e^{-i \gamma d}}{4\pi^2 a_0} \int b'_0(P) e^{-iK'P} dP.
\]
Fig. 1. Spherical near-field measurement geometry with reflecting plate (top view).

Fig. 2. Far field of 30 λ reflector antenna computed from measured near-field data illustrating the suppression of reflected signals. (a) 15 dB probe, no reflecting plate. (b) 5 dB probe, with reflecting plate. (c) 15 dB probe with reflecting plate.
Equation (2) yields one equation with two unknowns. Hence, one must apply a second probe or the same probe rotated 90° to obtain a second equation. Then for each K one can solve the system of two linear equations for S_o(K). The right side is computed independently of the probe pattern, and the probe correction enters through the coefficients S_b2(K) which actually are the probe receiving patterns as a function of K.

The probe correction concept for nonplanar scanning was originally introduced by Brown and Jull in a paper [10] on two-dimensional cylindrical scanning. The field component E, from the test antenna is expanded in a discrete spectrum:

\[ E_{\ell}(t, \theta, \phi) = \sum_{s=1}^{\infty} \sum_{m=-\infty}^{\infty} S_m \times m \times F_{s,m}(r, \theta, \phi) \]

where \( S_m \times m \times F_{s,m}(r, \theta, \phi) \) are the expansion coefficients with indices \( s, m, n \), where \( s = 1 \) for transverse electric (TE) modes and \( s = 2 \) for transverse magnetic (TM) modes. The \( F_{s,m}(r, \theta, \phi) \) are spherical wave functions as defined in [4]. The signal received by the probe in a spherical near-field measurement is expressed as

\[ W(A, \phi, \theta, \chi) = \sum_{s,m,n} \bar{Q}_{s,m,n} e^{im\phi} d_{\mu}^{m}(\theta) e^{iux} \phi_{s,m,n}(A) \]

in which \( W \) is the signal received in position \((\phi, \theta, \chi) \) at the measurement radius \( A \) and with \( \chi \) describing the polarization angle of the probe. \( e^{im\phi} d_{\mu}^{m}(\theta) e^{iux} \) are rotation coefficients of the spherical wave functions, and \( \phi_{s,m,n}(A) \) are spherical response constants, corresponding to \( c_s(b) \) above. They express the probe's sensitivity to the test antenna modes at the measuring radius \( A \) in the position \((\phi, \theta, \chi) = (0, 0, 0) \).

The probe is assumed to be sensitive to modes with \( \mu = \pm 1 \) only. Therefore, when orthogonality relations are applied to both sides of (7), a system of two linear equations is obtained

\[ \begin{bmatrix} F_{11,n}(A) & P_{21,n}(A) \\ P_{1, -1,n}(A) & P_{2, -1,n}(A) \end{bmatrix} \begin{bmatrix} Q_{1,m,n} \\ Q_{2,m,n} \end{bmatrix} = \begin{bmatrix} (\Delta P_{1,n}W)_{1,m} \\ (\Delta P_{2,n}W)_{2,1,m} \end{bmatrix} \]

in which

\[ (\Delta P_{\mu}W)_{\mu,m} = n + 1/2 \int_{-\infty}^{\infty} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} W(A, \phi, \theta, \chi) \times d_{\mu}^{m}(\theta) \sin \theta \ d\theta e^{-im\phi} d\phi e^{-iux} d\chi. \]

Again the integrals on the right side of (8) are computed independently of the probe pattern, and each pair of expansion coefficients \( \{Q_{1,m,n}, Q_{2,m,n}\} \) is the solution to a system of two equations with two unknowns. Then the far field can be evaluated by use of (6) with \( r = \infty \) or (7) with \( A = \infty \).

Comparing the three techniques we see that what they have in common is that some integral transformation is applied to the measured data, and this transformation separates the contributions to each pair of modes. The integral transformation is independent of the probe pattern as pointed out by Wacker [3]. Thus the process of solving the equations, in which the response constants are coefficients, compensates for

1) the measurement distance;
2) the probe pattern.

Probe correction only implies that different response constants are applied for different probes. Hence, one might say that the solution of the expansion-coefficient equations (2), (5), and (8) makes the near-field measurement plus transformation equally sensitive to all of the modes (planar, cylindrical or spherical waves, respectively).

If, for certain modes, the response constants are small in amplitude, the determination of the corresponding expansion at the measuring radius \( b \). Probe correction enters the computation of the expansion coefficients \( a_n \) through the division of the measured and Fourier-transformed data by the response constants \( c_s(b) \), which depend on the probe pattern and \( b \).

Also in the three-dimensional spherical technique [9] a discrete spectrum arises

\[ E(r, \theta, \phi) = \sum_{s=1}^{\infty} \sum_{m=1}^{\infty} \sum_{n=-n}^{n} Q_{s,m,n} F_{s,m,n}(r, \theta, \phi) \]

where \( Q_{s,m,n} \) are the expansion coefficients with indices \( s, m, n \).
coefficients becomes unstable. In the planar technique each pair of
expansion coefficients and each pair of response constants
(for the test antenna and the probe, respectively) is associated
with a single far-field direction. Therefore the instabilities are
associated with nulls in the probe pattern and they are confined
to distinct directions in the computed far field. For nonplanar
expansions, instabilities will occur for certain modes only, and in
the far field the mode fields and hence the errors will generally
contribute in all directions.

IV. INVESTIGATION OF THE SPHERICAL
RESPONSE CONSTANTS

In this section the spherical response constants are computed
for various probes in order to identify possible instabilities in the
spherical probe correction.

First we shall note some properties of the spherical wave func-
tions $F_{smn}$ necessary for interpretation of the results. The max-
imum mode index $n_{\text{max}}$ in the spherical wave expansion for the
field excited by the test antenna is approximately $r_0$, where $r_0$
is radius of the smallest sphere (minimum sphere) surrounding
the antenna. Further, a mode with index $n$ can only be excited by an
antenna with $r_0 > n/k$. Therefore we can also use the term
minimum sphere in connection with a single spherical wave, and,
in the near-field to far-field transformation one only needs to
calculate response constants for $n \leq n_{\text{max}}$. Likewise, the max-
nimum mode index $r_{\text{max}}$ for the probe coefficients $P_{\mu\nu}$ is deter-
mined by the size of the probe.

The response constants are computed by the formula:

$$ P_{\mu\nu}(A) = \frac{1}{2} \sum_{n} C_{\nu\mu}(A)C_{\mu\nu} $$

where $C_{\nu\mu}(A)$ are translation coefficients used when expressing
the test antenna modes $F_{smn}$ in terms of modes $F_{\mu\nu}$ in the probe
coordinate system. $C_{\mu\nu}$ are receiving coefficients for the probe
in its own coordinate system.

In spherical near-field measurements a conical horn excited
by a TE$_{11}$ mode in a circular waveguide is used as probe, and
hence $P_{\mu\nu}$ and $P_{\mu\nu}(A)$ are nonzero for $\mu = \pm 1$ usually. Only
the probe is approximately linearly polarized in the E- and H-
planes. For such a probe, the matrix in (8) is nearly orthogonal,
and the solution process is well conditioned. With the addi-
tional requirement that the E-plane pattern is the same as the H-
plane pattern such that the polarization is the same as that of a Huygens
source, the matrix takes the form [6]:

$$
\begin{bmatrix}
P_{11\nu}(A) & P_{21\nu}(A) \\
P_{1,-1,\nu}(A) & P_{2,-1,\nu}(A)
\end{bmatrix} = \kappa_{\nu}(A) \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}
$$

and the condition number of the matrix is one. Our investiga-
tion is therefore concerned with the variation of $|\kappa_{\nu}(A)|$ as a function
of $n$, $A$, and probe directivity.

Two probes have been modelled as linear endfire arrays of
Huygens sources, c.f. Table I. These probes have been used be-
cause each Huygens source measures a combination of E- and H-
field components so that the received signal in the simulations
can be calculated exactly as a weighted sum over the array ele-
ments. The receiving patterns of the two probes are shown in
Fig. 3, and a series of curves of $|\kappa_{\nu}(A)|$ for the two probes is
shown in Figs. 4(a)-(f).

When the measurement range approaches infinity (correspond-
ing to far-field measurements), all spherical modes tend to appear
as plane waves with axial incidence on the probe. This means
that the variation of $|\kappa_{\nu}(A)|$ with $n$ follows the amplitude
of the individual modes on the z-axis. Our mode functions $F_{smn}$
are normalized so that the radiated power for each mode is
$1/2 |Q_{smn}|^2$ [4], and for $|m| = 1$ they satisfy

$$|krF_{smn}| \rightarrow \frac{k}{\sqrt{\eta}} \sqrt{\frac{2n + 1}{16\pi}}, \quad \text{for } kr \to \infty$$

where $\eta$ is the free space admittance. Accordingly, the two
curves in Fig. 4(f) are proportional to $\sqrt{2n + 1}$. The difference
between the curves is equal to the ratio of boresight gain for the
two probes.

At a finite distance the probe will still be in the far field of the
low order modes, i.e., for $n^2 < kA$. Hence the $\sqrt{2n + 1}$ variation
dominates the left parts of Figs. 4(a)–4(c).

In the right parts of Figs. 4(a) and 4(b) the curves increase
dramatically. Mathematically this is due to the spherical Hankel
functions $h^2_{\nu}(kA)$ in the translation coefficients $C_{\mu\nu}(A)$. Hankel
functions of order $p > n + 1$ are included and for
$|m| = 1$ these functions become large. Physically, $n_{\text{max}} + r_{\text{max}} > kA$
implies that the minimum spheres of the test antenna and the
probe intersect. This situation should be avoided in practical
measurements. On the other hand large response constants imply
that the mode contributions will be heavily attenuated in the
near-field far-field transformation. Thus they will not cause
instabilities in the computations, unless one transforms from the
measurement distance to a shorter distance. Here, there is a danger
of overflow during the computation of the response
constants.

For most of the curves we observe some "nulls" indicating

---

**Table I**

<table>
<thead>
<tr>
<th>Directivity</th>
<th>15 dB</th>
<th>21 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.25 $\lambda$</td>
<td>3.60 $\lambda$</td>
</tr>
<tr>
<td>Number of elements</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>$r_{\text{max}}$</td>
<td>14</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 3. Far-field radiation patterns for the probes specified in Table I.
Fig. 4. Graphs of the response constants $|\kappa_n(A)|$ for the two probes specified in Table 1 at various distances.
that the probe is insensitive to particular modes. The major feature of the Hankel functions for $kr < n^2$ is that the phase variation with $r$ is less than $2\pi$ per wavelength. To a first approximation the mode field can be described as having an angle of incidence $\theta$ to the probe axis, different from zero. Using an asymptotic expression for the phase variation [11, eq. (9.2.29)] one can calculate the radial component of the propagation vector:

$$k_r = \frac{d\theta n + 1/2}{dr} \approx \left(1 - \frac{n(n + 1)}{2(kr)^2}\right) k$$

and get the following expression for the angle on incidence:

$$\theta = \sin^{-1} \left( \sqrt{1 - \left(\frac{k_r}{k}\right)^2} \right) \approx \sin^{-1} \left( \frac{n(n + 1)}{kA} \right).$$

The above expression is close to the incidence angle of a ray from the edge of the minimum sphere given in Fig. 5.

When $\theta$ is calculated from $(n, A)$ corresponding to the first null of the curves for the 15 dB probe in Figs. 4(a), 4(b), and 4(c), we get 44.6°, 44.1°, and 44.5°, respectively. This is very close to the angle of the first null in the radiation pattern of the 15 dB probe, c.f. Fig. 3. Similarly, the other nulls in Figs. 4(a)-4(d) correspond to nulls in the probe patterns in Fig. 3.

For probe corrected cylindrical near-field measurements, Borgiotti [12, 13] has shown that if the test antenna can be assumed to be in the far field of the probe, then the response constants can be calculated by a saddle point integration and each response constant will depend on the probe pattern in one direction only. Because of the appearance of a Legendre function in the formulas for the spherical waves, a similar derivation has not been possible in the spherical case; but Figs. 4(a)-4(e) illustrate that the probe receiving patterns via the concept of incidence angle are reflected in the curves for the response constants. Only, the first null of the 21 dB probe changes to a "shoulder" in the $|k_n(A)|$ curves. As long as the minimum sphere of the test antenna lies within the main beam of the probe, instabilities will show up for $n > n_{max}$ only.

The disappearance of the first null for the 21 dB probe is caused by the distance to the minimum sphere of the corresponding modes (i.e., $A - n/k$) being smaller than the far-field distance of the probe. Thus the response constants are related to the probe pattern at the actual measurement distance rather than the far-field pattern. Computer simulations have verified that especially the first null tends to vanish at short distances. As an example, Fig. 5 corresponds to Fig. 4(c) for the 21 dB probe. The first null at $\theta = 25°$ would imply that only a sphere up to $n_{max} = 38$ could be used. However, since the first null has disappeared at this distance, antennas with $n_{max}$ up to 50 can be measured. In the extreme situation where the probe is larger than the test antenna, the situation is similar to a compact range measurement in which the far field is measured directly, and the response constants will therefore follow the curves in Fig. 4(f) without instabilities.

Summarizing, we have verified the existence of instabilities for the probe correction in the spherical technique, where error signals and noise could introduce errors in the computed far field. Such errors would arise through amplification of certain critical
modes and generally be “spread out” over the entire angular space. However, as long as the probe illuminates the entire minimum sphere of the test antenna, the instabilities appear outside the mode range necessary to represent the test antenna field. Errors can therefore be avoided by proper truncation of the expansion for the test antenna field. Further, since the response constants are always computed as a part of a far-field transformation, instabilities can be detected in the computer program.

V. CONCLUSION

In spherical near-field measurements a directive probe increases the direct signals from the test antenna and suppresses reflected signals from outside the test antenna volume. The probe correction in the subsequent data processing compensates for the probe pattern variation over the test antenna aperture. Theoretical investigations have shown that numerical instabilities may arise for certain critical modes. However, as long as the probe illuminates the entire test antenna volume, these instabilities will correspond to directions from outside the test antenna. Accordingly, they can be avoided by proper truncation of the spherical wave expansion for the test antenna field. Measurements have verified that signals received from the surroundings will not be amplified by the probe correction.

It should be emphasized that the results above do not apply to multiple reflections between the test antenna and the probe. In general these reflections will increase with increasing size of the probe, and this effect can in some cases put a limit on the feasible probe size.

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REFERENCES


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