Near Field Measurement Errors Due To Neglecting Probe Cross-Polarization  

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ABSTRACT
Calibration of planar near field probes is generally required to obtain accurate cross-polarization measurements of satellite antennas; however, probe calibration is costly and time consuming. One way to avoid probe calibration is to ignore the probe cross-polarization and use the probe co-polarized patterns alone for probe correction. Then the probe can be easily characterized by standard, in-house measurements or by analytical models. Of course, if the probe cross-polarization is ignored, additional errors are introduced in the co- and cross-polarized pattern measurements, but the errors can be manageable, depending on the probe and Antenna-Under-Test (AUT) polarization properties. Complete formulas and/or tables for near field measurement errors for three popular measurement configurations are presented, along with experimental verification of the error estimates for one case.

Keywords: Near Field Cross Polarization Measurements, Near Field Probe

1.0 Introduction
Planar near field (NF) ranges are often used for satellite antenna measurements, because most satellite antennas have high-gain, narrow beams, and the measurements can be performed in an environmentally controlled, indoor facility, 24/7, if necessary. However, many satellite antennas operate with extremely low (-30 to -40 dB) cross-polarization ratios, which usually require probe calibration to obtain accurate results. Allen Newell [1] developed a systematic method to assess near field measurement errors that is often used to certify ranges. In his paper, Newell lists 18 error terms, including probe correction errors.

Probe correction is performed in the far field by algebraically combining the probe’s far field pattern with the Fourier transform of near field measurements of the Antenna-Under-Test (AUT), to produce the AUT’s true far field pattern. Following Newell’s notation, the AUT co-polarized (copol) pattern, \( t_m \), and cross-polarized (xpol) pattern, \( t_c \), are computed from two NF scans using the following expressions:

\[
t_m = \frac{D'}{s_m} - \frac{D''}{s_m} \cdot \rho'_c
\]

\[
t_c = \frac{D''}{s_c} - \frac{D'}{s_c} \cdot \rho''_m
\]

where the subscript \( m \) refers to the main or co-polarized component and subscript \( c \) refers to the cross-polarized component. \( D' \) and \( D'' \) are the Fast Fourier Transforms (FFTs) of the first and second scans, respectively, \( s'_m \) and \( s'_c \) are the probe patterns, and \( \rho'_c \) and \( \rho''_m \) are the probe polarization ratios for each of the two scans. In general, the probes are chosen such that the probe for the first scan couples primarily to the \( m \)-component, and the probe for the second scan couples primarily to the \( c \)-component, so the FFT of the first scan, \( D' \), is mostly copol and \( D'' \) is mostly xpol, and \( D' \) is usually >> \( D'' \). The probe polarization ratios are also defined such that and \( \rho'_c < 1 \) and \( \rho''_m > 1 \). All terms are complex functions of far field angles, theta and phi.

If we assume the probe xpol is zero, \( \rho'_c \to 0 \) and \( \rho''_m \to \infty \), and equations (1) and (2) for the AUT copol and xpol are approximated by the simple expressions,

\[
t_m \cong \frac{D'}{s_m}
\]

\[
t_c \cong \frac{D''}{s_c}
\]

Here, we essentially assume the first (copol) scan measures only copol signals and the second scan is entirely xpol.

The copol approximation of equation (3) is generally valid, because, in most cases, the \( D' \) copol term dominates equation (1) and the \( D'' \) xpol term can be ignored. However, in xpol equation (2), the \( D'' \) xpol term can be comparable to the \((D'/\rho''_m)\) term. Since the probe responds to both co- and cross-polarization signals, the FFT of the measured near field is a combination of the true AUT xpol and some of the AUT copol, and the probe patterns are often required to separate the components. For the highest accuracy measurements, probes are usually sent to a calibration laboratory, where the probe’s amplitude and phase patterns are meticulously measured to create probe cal-files that are used to process the AUT measurements. This calibration process generally costs thousands of dollars and can take weeks or even months.
In Newell’s paper, he presents AUT xpol measurement errors due to errors in the probe correction patterns, when the AUT and probe are both linearly polarized or both circularly polarized (including the case where the probe xpol is entirely neglected). Newell assumes the probe pattern errors are in amplitude only with zero phase error. However, probe xpol phase measurements can be difficult to make, especially when the probe has a fairly low xpol level. Figure 1 shows that phase errors can make the AUT errors even larger than presented by Newell, even with zero amplitude error. From the antenna test engineer’s perspective, it is easier to assume the probe xpol is zero and use measured or analytical probe copol patterns for correction, avoiding the expense and time required for probe calibration.

2.0 Three Common Near Field Range Measurements

Three common polarization situations encountered during near field range measurements of an Antenna-Under-Test (AUT) and a Standard Gain Horn (SGH) are:

- Case-1: Linear AUT, Linear Probe, Linear SGH
- Case-2: CP AUT, CP Probe, Linear SGH
- Case-3: CP AUT, Linear Probe, Linear SGH

In Case-1, a linearly polarized AUT and Standard Gain Horn (SGH) are measured with two scans of a linear probe. Xpol ratio measurement errors resulting from ignoring probe xpol are given by Newell [1] as:

\[ \rho_{c-e} = 1 + \frac{1}{\rho_t \cdot \rho_s'} \]

where \( \rho_{c-e} \) = apparent AUT xpol ratio, \( \rho_t \) = true AUT xpol ratio, and \( \rho_s' \) is the probe polarization ratio defined earlier (Recall that \( \rho_t < 1 \) and \( \rho_s' > 1 \)). The apparent AUT xpol ratio can be larger or smaller than the true xpol ratio, depending on the relative phase of the AUT and probe polarization ratios.

Table 1 is a tabulation of AUT xpol ratio measurement errors as a function of the ratio of the probe xpol ratio to AUT xpol ratios. Note that the probe xpol ratio needs to be significantly better than the AUT to get accurate results. For example, a -40 dB probe has a possible error range of +2.4 to -3.3 dB when measuring a -30 dB AUT. Note that when the probe and AUT xpol ratios are equal in magnitude, the apparent AUT xpol ratio can be 6 dB higher or cancel completely, depending on the relative phase.

Table 1 – Xpol Ratio (XPR) Measurement Errors for Linear AUTs and Linear Probes

<table>
<thead>
<tr>
<th>Probe XPR - AUT XPR (dB)</th>
<th>Apparent XPR – True AUT XPR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
</tr>
<tr>
<td>-20</td>
<td>0.8</td>
</tr>
<tr>
<td>-15</td>
<td>1.4</td>
</tr>
<tr>
<td>-10</td>
<td>2.4</td>
</tr>
<tr>
<td>-5</td>
<td>3.9</td>
</tr>
<tr>
<td>0</td>
<td>6.0</td>
</tr>
<tr>
<td>5</td>
<td>8.9</td>
</tr>
<tr>
<td>10</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Newell’s analysis method can be extended to copol errors by computing the ratio of equation (3) to equation (1). The AUT or SGH copol measurement error is then given by:

\[ t_{m-e} = 1 + \rho_t \cdot \rho_s' \]

where \( t_{m-e} \) = apparent AUT copol pattern assuming equation (3) and \( t_m \) = true AUT copol pattern. Since, both \( \rho_t \) and \( \rho_s' \) are usually << 1, copol measurement errors of less than 0.1 dB are easily obtained with most probes, validating the approximation of equation (3).

In Case-2, we use a CP probe to scan a CP AUT and a linear SGH. If we follow the same analytical method as before, we reach the same conclusion as Newell: namely that the AUT axial ratio (AR) measurement error equals the maximum probe AR over the field-of-view (e.g. to get 0.2 dB of AR measurement accuracy, we need a probe with 0.2 dB AR).
Copol errors can be derived with the same process used for the linear polarized probes. Table 2 shows that, like Case-1, the copol errors are generally negligible, except for the linear SGH, which is surprisingly sensitive to the probe AR. Note that a probe with a 1 dB axial ratio can have a 0.5 dB error when measuring a linear gain horn.

Table 2 – Maximum Copol Measurement Errors (dB) for CP AUTs and CP Probes

<table>
<thead>
<tr>
<th>AUT AR (dB)</th>
<th>0.2 dB</th>
<th>0.5 dB</th>
<th>1.0 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>0.5</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>1.0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>1.5</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>2.0</td>
<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>3.0</td>
<td>0.02</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Linear</td>
<td>0.10</td>
<td>0.25</td>
<td>0.49</td>
</tr>
</tbody>
</table>

In Case-3, we use two linear probe scans to measure a CP AUT and a linear SGH. We no longer have the problem of measuring a small xpol signal in the presence of a large copol signal. Instead, the linear copol and xpol components are about the same magnitude, but with a 90 degree phase difference. If we remove some of the approximations assumed by Newell, the ratio of the linear components will be in error by:

\[ \rho_{i+s} = \frac{1 - \rho_i^s \cdot (1 + \rho_s \cdot \rho_i^s)}{\rho_i \cdot (\rho_i^s - \rho_s^s)} \cdot \frac{1}{1 + \rho_i \cdot \rho_i^s} \]

The maximum axial ratio errors from equation (7) are show in Table 3, assuming worst case phase combination of the polarization ratios and assuming that the probe xpol ratio for the first scan is equal to the probe xpol ratio for scan-2 (i.e. \( |\rho_i^s| = |1/\rho_i^s| \)), which is generally true if the same probe is used for both scans.

Table 3 – Maximum AR Measurement Errors (dB) for CP AUTs and Linear Probes

<table>
<thead>
<tr>
<th>AUT Axial Ratio (dB)</th>
<th>-40 dB</th>
<th>-30 dB</th>
<th>-25 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.17</td>
<td>0.55</td>
<td>0.98</td>
</tr>
<tr>
<td>0.5</td>
<td>0.17</td>
<td>0.55</td>
<td>0.98</td>
</tr>
<tr>
<td>1.0</td>
<td>0.18</td>
<td>0.56</td>
<td>0.99</td>
</tr>
<tr>
<td>1.5</td>
<td>0.18</td>
<td>0.56</td>
<td>1.00</td>
</tr>
<tr>
<td>2.0</td>
<td>0.18</td>
<td>0.57</td>
<td>1.02</td>
</tr>
<tr>
<td>3.0</td>
<td>0.18</td>
<td>0.59</td>
<td>1.06</td>
</tr>
</tbody>
</table>

As in the CP probe case, good probe polarization performance is required to obtain good accuracy for AUTs with low ARs, but in this case, the linear probe approach may be a good alternative to the CP probe, because low xpol linear probes are, in general, easier to fabricate than CP probes with low axial ratio, and the SGH errors are also lower. Of course the amplitude and phase difference between the two scans must be measured accurately.

3.0 Experimental Verification

As an example, we looked at the measured polarization ratio of a Ku-band linearly polarized AUT measured with a calibrated linear probe. The probe was a Potter-type [2] multimode conical horn designed specifically to measure this AUT. The probe copol and xpol patterns are almost constant over the FF angular range with the xpol level at about -42 dB. The AUT was measured in a 22-ft horizontal NF range, and we processed the NF data twice: (1) with the original calibrated copol and xpol probe patterns and (2) using an analytical model of the probe copol with the probe xpol assumed to be zero. Figures 2 and 3 are pattern plots of the AUT beam and the probe. Note that the AUT is pointed about 7.5° from the range boresight.

As expected, the AUT copol pattern processed without probe xpol (Figure 2) is almost identical to the pattern processed with the calibrated files. However, the AUT xpol patterns (Figure 3) differ somewhat, especially near boresight. The corresponding xpol ratios for the probe and two AUT patterns are plotted in Figure 4 over an angular range that includes the main beam and the first few sidelobes. In the sidelobe region, the AUT xpol ratio is large compared to the probe, and we get a good match between the AUT patterns with and without probe xpol. The match is not as good in the main beam, especially when the probe xpol ratio is greater than the AUT.

Taking the difference between the AUT with and without probe xpol as the measurement error, Figure 5 shows the error plotted along with the max and min errors predicted by equation (5). The measured data follows the predicted envelope rather closely, validating our Case-1 error estimates for ignoring the probe xpol.

4.0 Summary and Conclusions

Errors associated with ignoring the probe xpol were discussed and demonstrated experimentally. Low copol errors can be easily obtained, but the probes must have very good polarization properties to get accurate xpol ratio results.

Formulas and/or tables with the copol and xpol errors were presented for three of the most commonly used polarization combinations. General conclusions:

- Copol errors of < 0.1 dB can be easily obtained.
• The probe xpol ratio needs to be significantly better than the AUT xpol to get accurate xpol results. A probe with a -40 dB xpol ratio has a possible error of +2.4, -3.3 dB when used to measure a -30 dB AUT.

For CP AUT/CP Probe/Linear SGH combinations:
• Copol errors of < 0.1 dB can be easily obtained.
• Ignoring the probe xpol can add significant errors to the SGH scans. The probe AR should be < 0.5 dB to keep the errors from dominating the SGH error budget.
• The max AR error is equal to the AR of the probe. A probe with a 0.2 dB AR will have a 0.2 dB AR measurement error.

For CP AUT – Linear Probe – Linear SGH combinations:
• Copol errors of < 0.1 dB can be easily obtained.
• As in the CP probe case, good probe polarization performance is required to obtain good accuracy for AUTs with low AR. A probe with a -40 dB xpol ratio will have only 0.17 dB AR error.
• The linear probe approach is a good alternative to the CP probe, because low xpol linear probes are, in general, easier to fabricate than CP probes with low axial ratio, and the SGH errors are also lower.

5.0 REFERENCES

![Figure 2 – Measured (calibrated) probe patterns and AUT copol NF measurements processed with and without probe xpol](image-url)
Figure 3 – Measured (calibrated) probe patterns and AUT xpol NF measurements processed with and without probe xpol

Figure 4 – Probe and AUT xpol ratios from NF measurements processed with and without probe xpol

Figure 5 – Measured AUT xpol ratio error and error estimate range from equation (5)