

Correcting Polarization Distortion in a Compact Range Feed

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Abstract—A high quality antenna feed is an essential element of a compact antenna test range (CATR) in order to ensure the range can achieve the necessary stability in beam width, phase center and the necessary purity of polarization throughout the range’s quiet zone. In order to maintain the requisite quality, such feeds are typically 1) single-port and 2) cover a relatively limited band of frequencies. It is desirable to have a single dual ported, broadband feed that covers multiple waveguide bands to eliminate the need for a polarization positioner and avoid the difficulty associated with changing feeds for a single antenna measurement. Though some such feeds exist in the market, with such feeds, we often see a reduction in polarization purity across the band of interest relative to the more band limited feeds. Previous attempts to utilize dual-port probes and/or extend the bandwidth of the feed have resulted in degraded performance in terms of beam pattern and polarization purity. In an attempt to overcome some of the deficiencies above, the authors have applied polarization processing to dual-pol antennas to correct for the impurity in polarization of the antenna as a function of frequency. We present here a broadband CATR feed solution using a low-cost, dual-port sinuous feed structure combined with polarization processing to achieve low cross-pol coupling throughout the quiet zone. In the following paper, the feed structure, polarization theory, and processing algorithm are described. We also present co- and cross-pol coupling results before and after correcting for the polarization distortion using data collected in two CATRs in Atlanta, GA and Asia.

Index Terms—Compact Range, Cross Polarization Distortion Correction, Broadband Dual-Port Feed

I. INTRODUCTION

In a compact range, amplitude and phase variation/taper and cross polarization are important, especially for multi-polarization measurements. The most commonly used single reflector range feeds are based on an open ended circular waveguide with an appropriate corrugated choke flange [1,2]. These feeds provide the desired quiet zone performance, but are limited in frequency to somewhat less than the standard waveguide bands and often require several feeds to cover the wideband response of an antenna under test (AUT). For wider frequency band measurements, dual-ridge and quad-ridge horns can be used as feeds, but these exhibit larger variations in amplitude and phase in the quiet zone as well as a shift in the phase center as a function of frequency which impacts the focus [3]. Sinuous antennas also provide wider frequency performance, but without the phase center movement. Unfortunately, they also exhibit poor cross-polarization

performance due, in large part, to a polarization rotation with frequency [4].

In this paper, we explore a broadband feed solution composed of a dual-pol sinuous feed with a polarization correction function to correct for the impure polarization of the feed. The bulk of this paper is devoted to the development of this polarization correction algorithm.

Section II describes the structure and behavior of the proposed sinuous feed. Section III reviews the theory of polarization states, enabling the derivation of a polarization transformation algorithm in Section IV. Section V presents test results of the algorithm in two different CATRs followed by a brief summary in Section VI.

II. DUAL-PORT FEED DESCRIPTION

A sinuous antenna is a planar log-periodic structure that offers relatively broadband response at the expense of an oscillation in the tilt of the polarization ellipse as a function of frequency [5]. For some applications, the oscillation is acceptable, but in antenna measurement applications where cross-polarization is an important test metric, this phenomenon is problematic.

The authors used a dual-polarized sinuous antenna in this study. A photograph of the antenna’s radiating elements is shown in Figure 1.



Figure 1. Photo of dual-port sinuous feed antenna

Different portions of the sinuous structure are resonant at different frequencies. As the frequency changes, the portions of the structure that are resonant rotate in angle yielding a polarization tilt that oscillates. The antenna was measured in a compact range in Atlanta, GA and its polarization parameters

were computed from the resultant data. The measured tilt of the antenna's horizontally oriented port is shown in Figure 2 at 10 measured frequencies from 1.7 to 2.6 GHz. The concept of tilt will be more formally defined in Section III.E.

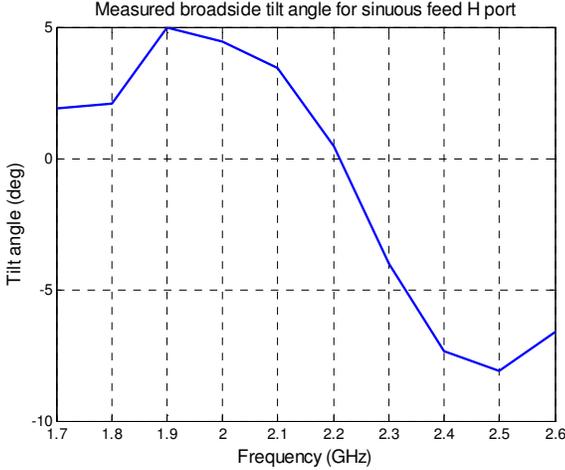


Figure 2. Measured polarization tilt of sinusoidal feed H port

Notice the oscillation of the tilt vs. frequency. This tilt, as it deviates from zero, introduces energy into the cross-polarization term. This tilt must be removed if a sinusoidal antenna such as this were to be used in a compact range to ensure polarization purity in the quiet zone (QZ) to allow for accurate measurement of AUT cross-polarization.

III. POLARIZATION THEORY

In this section, we describe five different representations of polarization state of an electromagnetic wave. This provides the necessary theoretical background to develop the polarization correction algorithm in the following section.

A. Jones Vectors

Assuming the existence of two orthogonal polarizations (P_1 and P_2), the 2×1 Jones vector [6] is given as the complex amplitudes of signals at those two polarizations given the presence of a signal of some arbitrary polarization P_0 . Thus, the two polarizations comprising the Jones vector act as orthogonal basis functions representing a complete 2-dimensional space that completely describes the polarization state of the wave. Typically P_1 is assumed to be horizontal and P_2 is vertical, but that is not necessary; any two orthogonal polarizations will work equally well. The Jones vector may be written as [6]

$$E = \begin{bmatrix} E_{P_1} \\ E_{P_2} \end{bmatrix} = \begin{bmatrix} a_1 e^{j\phi_1} \\ a_2 e^{j\phi_2} \end{bmatrix} = a_0 e^{j\phi_1} \begin{bmatrix} \cos \gamma \\ e^{j\eta} \sin \gamma \end{bmatrix} \quad (1)$$

where $\tan \gamma = \frac{a_2}{a_1}$ is the ratio of the magnitudes of the two elements of the Jones vector and $\eta = \phi_2 - \phi_1$ is the difference between the phases of the two elements.

The (γ, η) pair also completely describes the polarization state. Note that these values are invariant to phase and magnitude shifts applied to both elements of the Jones vector simultaneously. A change in signal power (a_0) does not

change the polarization and an absolute phase shift ($e^{j\phi_1}$) in the received signal does not change the polarization.

The Jones vector may also be thought of as the vector of complex voltages received at a dual polarized antenna in the presence of an electromagnetic wave. The basis polarizations are the polarizations of the two ports and the polarization state projected onto those bases is one representation of the polarization of the EM wave incident on the antenna. We begin our treatment with the Jones vector because it is most closely tied to the measurement domain.

B. Complex Polarization Ratio

The (γ, η) pair of parameters may be represented succinctly by the complex polarization ratio, ρ , given by the ratio of the two complex elements of the Jones vector [7],

$$\rho = \frac{E_{P_2}}{E_{P_1}} = e^{j\eta} \tan \gamma \quad (2)$$

This ratio contains the same information as the first representation, but is sometimes preferred as it is somewhat more compact. Notice the magnitude of this parameter is related to γ while the phase is equal to η .

C. Stokes Parameters

From the Jones vector, another vector of three or four parameters can be computed that represents a set of basis projections of the polarization state onto V/H, +45/-45, and RHCP/LHCP [8]. Assuming the Jones vector uses the standard H/V basis polarizations ($E_{P_1} = E_H$ and $E_{P_2} = E_V$), the Stokes parameters are given by the following equations.

$$\begin{aligned} S_0 &= |E_H|^2 + |E_V|^2 = a_1^2 + a_2^2 \\ S_1 &= |E_H|^2 - |E_V|^2 = a_1^2 - a_2^2 \\ S_2 &= 2\text{Re}\{E_H^* E_V\} = 2a_1 a_2 \cos(\phi_1 - \phi_2) \\ S_3 &= 2\text{Im}\{E_H^* E_V\} = 2a_1 a_2 \sin(\phi_1 - \phi_2) \end{aligned} \quad (3)$$

The first of the four Stokes parameters is the intensity or power of the electromagnetic wave and is only important if one is concerned with partial polarization. For this paper, we are only concerned with fully polarized EM waves and so the first element is effectively eliminated by computing the three normalized Stokes parameters given below.

$$s_1 = \frac{S_1}{S_0}, s_2 = \frac{S_2}{S_0}, s_3 = \frac{S_3}{S_0} \quad (4)$$

The values of the normalized Stokes parameters for six common polarization states are given below [8, p.23].

TABLE I. NORMALIZED STOKES PARAMETER VALUES FOR SIX COMMON POLARIZATION STATES

	s_1	s_2	s_3
Horizontal	1	0	0
Vertical	-1	0	0
+45	0	1	0
-45	0	-1	0
RHCP	0	0	1
LHCP	0	0	-1

D. Poincaré Sphere

The Poincaré sphere [9] is a useful visualization tool for representing any polarization state referenced to the basis functions H/V. These basis functions can be rotated to any other set of orthogonal basis functions, but this choice is sufficient to illustrate the concepts here. Assuming a fully polarized signal, the polarization state of an EM wave is given in Cartesian coordinates by (s_1, s_2, s_3) . It is also given in spherical coordinates of $(1, \frac{\pi}{2} - 2\chi, 2\psi)$ where the angular parameters χ and ψ (radians) are shown in Figures 4-5 below.

For normalized Stokes parameters, the Poincaré sphere is a unit radius sphere centered at the origin. Fully polarized signals lie on the surface of the sphere while partially polarized signals lie on the interior of the sphere with the origin representing a completely unpolarized wave.

A view of the sphere is given in Figure 3 showing a single polarization state P_0 and the sphere's relationship to the Stokes parameters and the angular parameters (γ, η) described above [10, p. 38]. The angle 2γ is the angle subtended by $(1,0,0)$ and P_0 along a great circle passing through P_0 and the S_1 axis. The angle η is the angle this great circle makes with the $S_3 = 0$ plane.

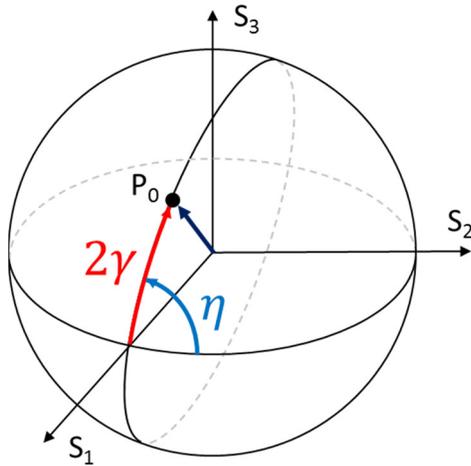


Figure 3. Graphical depiction of Poincaré sphere showing γ and η

Based on the table of Stokes parameters above, one can surmise some basic properties of the Poincaré sphere. The value $(1,0,0)$ represents horizontal polarization with the orthogonal polarization (vertical) at the opposite point of the sphere $(-1,0,0)$. The $\pm 45^\circ$ polarizations lie on the equator offset from V/H by 90° . The equator represents all possible linear polarizations. The north pole represents RHCP and the south pole represents LHCP.

E. Elliptical Parameters

The polarization parameters of axial ratio, tilt, and sense are derived from the ellipse traced by the electric field component of the EM wave at a single point in space as it propagates in time away from the observer. Figure 4 shows the ellipse and the elliptical parameters [8, p.6]. Two thin black lines show the major and minor axes of the ellipse, χ is

related to the semi-major and semi-minor axes, ψ is the tilt the ellipse makes with the x-axis, and the black arrows indicate the sense or direction the electric field traces as a function of time (clockwise = RH = +1 or counterclockwise = LH = -1).

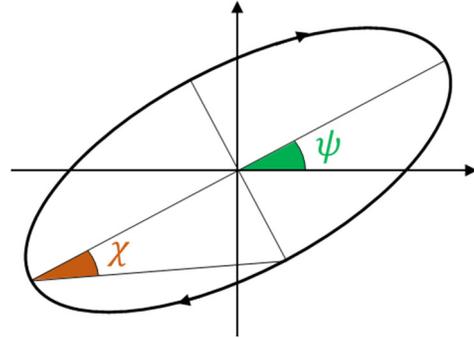


Figure 4. General form of polarization ellipse

Another view of the Poincaré sphere is given in Figure 5 [8, p.16-17] showing the sphere's relationship to the elliptical parameters χ and ψ . In this figure, a great circle is shown passing through P_0 and the S_3 axis with angle defined as shown.

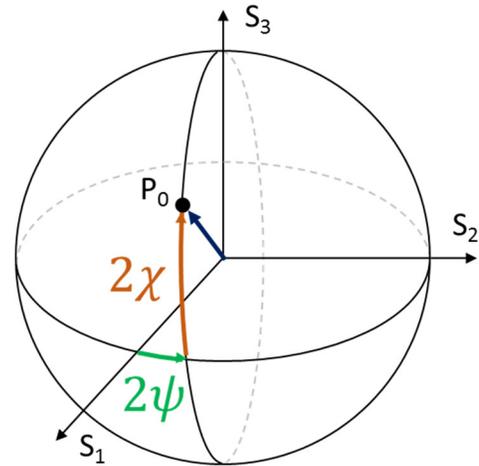


Figure 5. Poincaré sphere with χ and ψ

From Figure 5, the following relationships are evident.

$$\begin{aligned} \tan 2\chi &= \frac{s_3}{\sqrt{s_1^2 + s_2^2}} \\ \tan 2\psi &= \frac{s_2}{s_1} \end{aligned} \quad (5)$$

The axial ratio, defined as the ratio of the polarization ellipse's major and minor axes and denoted here as β , can be computed from χ as

$$\beta = \cot \chi \quad (6)$$

The tilt, denoted here as ψ , is given by

$$\psi = \frac{1}{2} \tan^{-1} \frac{s_2}{s_1} \quad (7)$$

The sense, denoted here as σ , is given by

$$\sigma = \text{sign}(s_3). \quad (8)$$

IV. POLARIZATION CORRECTION

In this section, we derive an algorithm for transforming from one set of polarization basis functions to another. This allows us to use the sinuous feed ports to synthesize a polarization that matches that of a more purely polarized reference antenna. The derivation begins with a general treatment of polarization rotation and then, using zero forcing on the cross-pol terms, the polarization transformation function is formulated.

A. Polarization Rotation

1) Two-Step Rotation

Using a pair of orthogonal basis polarizations, a wave's polarization can be rotated to any other arbitrary polarization. This is done by considering the (γ, η) representation of the Jones vector and de-rotating η , then γ to convert the polarization to the first basis polarization (typically horizontal). The horizontally polarized wave can then be rotated to an arbitrary polarization defined by (γ_0, η_0) by forward rotating γ_0 and then η_0 as follows.

Using the formula of E from (1), the de-rotated Jones vector is given by

$$E_1 = \begin{bmatrix} \cos \gamma & \sin \gamma \\ -\sin \gamma & \cos \gamma \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{-j\eta} \end{bmatrix} E = a_0 e^{j\phi_1} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (9)$$

Multiplying the Jones vector by a complex number does not affect the polarization state, so this is pure P_1 . The forward rotated Jones vector is then given by

$$E_0 = \begin{bmatrix} 1 & 0 \\ 0 & e^{j\eta_0} \end{bmatrix} \begin{bmatrix} \cos \gamma_0 & -\sin \gamma_0 \\ \sin \gamma_0 & \cos \gamma_0 \end{bmatrix} E_1 = a_0 e^{j\phi_1} \begin{bmatrix} \cos \gamma_0 \\ e^{j\eta_0} \sin \gamma_0 \end{bmatrix} \quad (10)$$

Notice that when $\gamma = \gamma_0$ and $\eta = \eta_0$, the forward and reverse rotations lead us to the same polarization we started with. Under these conditions, the de-rotation matrix

$$R^*(\gamma, \eta) = \begin{bmatrix} \cos \gamma & e^{-j\eta} \sin \gamma \\ -\sin \gamma & e^{-j\eta} \cos \gamma \end{bmatrix} \quad (11)$$

is the Hermitian transpose AND inverse of the forward rotation matrix

$$R(\gamma, \eta) = \begin{bmatrix} \cos \gamma & -\sin \gamma \\ e^{j\eta} \sin \gamma & e^{j\eta} \cos \gamma \end{bmatrix}. \quad (12)$$

By this means, any arbitrary polarization may be rotated to any other. This rotation affects both the tilt and axial ratio of the polarization ellipse and both parameters may be fixed to any values we choose.

2) One-Step Rotation

The inverse rotation may also be performed by setting

$$\tilde{\gamma} = \tan^{-1} \left(\frac{E_2}{E_1} \right) = \tan^{-1} \left(\frac{a_2}{a_1} e^{j\eta} \right) = \tan^{-1}(\tan(\gamma) e^{j\eta}) \quad (13)$$

$$= \tan^{-1}(\rho)$$

such that $\tilde{\gamma}$ is complex and then applying a simple de-rotation matrix

$$R^*(\tilde{\gamma}) = \begin{bmatrix} \cos \tilde{\gamma} & \sin \tilde{\gamma} \\ -\sin \tilde{\gamma} & \cos \tilde{\gamma} \end{bmatrix}. \quad (14)$$

A forward rotation may similarly be defined as

$$R(\tilde{\gamma}) = \begin{bmatrix} \cos \tilde{\gamma} & -\sin \tilde{\gamma} \\ \sin \tilde{\gamma} & \cos \tilde{\gamma} \end{bmatrix}. \quad (15)$$

B. Polarization Transformation

Each rotation effectively transforms the polarization basis functions from one set to another. Assuming the existence of a Polarization Standard with trusted polarization characteristics, we can measure the Jones vector of the sinuous feed and de-rotate the Jones vector using (14) as follows:

$$\tilde{\gamma}_1 = \tan^{-1} \left(\frac{E_B^{(1)}}{E_A^{(1)}} \right) = \tan^{-1} \left(\frac{a_2^{(1)}}{a_1^{(1)}} e^{j\eta^{(1)}} \right) \quad (16)$$

$$E_1 = \begin{bmatrix} \cos \tilde{\gamma}_1 & \sin \tilde{\gamma}_1 \\ -\sin \tilde{\gamma}_1 & \cos \tilde{\gamma}_1 \end{bmatrix} E^{(1)} = a_0^{(1)} e^{j\phi_1^{(1)}} \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \quad (17)$$

The superscript (1) indicates values obtained when the reference antenna is polarized as P_1 and

$$E^{(1)} = \begin{bmatrix} E_A^{(1)} \\ E_B^{(1)} \end{bmatrix} \quad (18)$$

is the measured two-element Jones vector corresponding to ports A and B of the dual-port sinuous antenna.

If the Polarization Standard is horizontally polarized, the de-rotation in (17) will rotate the secondary polarization of the Jones vector to reference vertical. This is clear as the value of that element has been forced to zero, so it represents a perfect cross-polarization to the standard. Ideally, this would mean that the primary polarization is now reference horizontal, but that may not be true if the antenna's original basis functions are not perfectly orthogonal.

In order to ensure a purely horizontal polarization has been obtained as one of the basis functions, a polarization standard that is purely vertical is required. If the resultant Jones vector is measured, then a similar de-rotation may be applied followed by a forward rotation to the opposite side of the Poincaré sphere to yield

$$\tilde{\gamma}_2 = \tan^{-1} \left(\frac{E_B^{(2)}}{E_A^{(2)}} \right) = \tan^{-1} \left(\frac{a_2^{(2)}}{a_1^{(2)}} e^{j\eta^{(2)}} \right) \quad (19)$$

$$E_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \cos \tilde{\gamma}_2 & \sin \tilde{\gamma}_2 \\ -\sin \tilde{\gamma}_2 & \cos \tilde{\gamma}_2 \end{bmatrix} E^{(2)} = \begin{bmatrix} \sin \tilde{\gamma}_2 & -\cos \tilde{\gamma}_2 \\ \cos \tilde{\gamma}_2 & \sin \tilde{\gamma}_2 \end{bmatrix} E^{(2)} \quad (20)$$

$$= a_0^{(2)} e^{j\phi_1^{(2)}} \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

In this case, the primary pol is forced to zero. If P_2 is vertical, the primary pol of the rotated Jones vector must now be reference horizontal. By combining the first row of the de-rotation matrix in (17) with the second row of the de-rotation matrix in (20), we obtain a transformation matrix that takes an arbitrary set of polarization basis functions and converts them to another arbitrary set. If based on a Polarization Standard

such as a standard gain horn (SGH) oriented vertically and then rotated to horizontal, a very clear V/H polarization pair is obtained. The transformation matrix is thus defined as

$$\begin{bmatrix} H_{REF} \\ V_{REF} \end{bmatrix} = \begin{bmatrix} \sin \tilde{\gamma}_2 & -\cos \tilde{\gamma}_2 \\ -\sin \tilde{\gamma}_1 & \cos \tilde{\gamma}_1 \end{bmatrix} \begin{bmatrix} E_A \\ E_B \end{bmatrix} \quad (21)$$

where $\tilde{\gamma}_1$ and $\tilde{\gamma}_2$ are given by (16) and (19) respectively.

This polarization transformation is not a simple rotation, though it began as one. Rather than simply rotating the Poincaré sphere to a new reference point, it distorts the surface of the sphere, stretching it in some areas and compressing it in others as it changes the orthogonality of the basis functions.

The transformation above can be re-written in terms of the original Jones vector elements by noting the relationships

$$\alpha_1 \equiv a_0^{(1)} e^{j\phi_0^{(1)}} = \frac{E_A^{(1)}}{\cos \tilde{\gamma}_1} = \frac{E_B^{(1)}}{\sin \tilde{\gamma}_1} \quad (22)$$

$$\alpha_2 \equiv a_0^{(2)} e^{j\phi_0^{(2)}} = \frac{E_A^{(2)}}{\cos \tilde{\gamma}_2} = \frac{E_B^{(2)}}{\sin \tilde{\gamma}_2} \quad (23)$$

Re-writing (21), we obtain the final solution of the polarization transformation matrix

$$\begin{aligned} \begin{bmatrix} H_{REF} \\ V_{REF} \end{bmatrix} &= \begin{bmatrix} \frac{E_B^{(2)}}{\alpha_2} & -\frac{E_A^{(2)}}{\alpha_2} \\ -\frac{E_B^{(1)}}{\alpha_1} & \frac{E_A^{(1)}}{\alpha_1} \end{bmatrix} \begin{bmatrix} \tilde{E}_A \\ \tilde{E}_B \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ \sqrt{E_A^{(2)^2 + E_B^{(2)^2}} & 0 \\ 0 & \frac{1}{\sqrt{E_A^{(1)^2 + E_B^{(1)^2}}} \end{bmatrix} \begin{bmatrix} E_B^{(2)} & -E_A^{(2)} \\ -E_B^{(1)} & E_A^{(1)} \end{bmatrix} \begin{bmatrix} \tilde{E}_A \\ \tilde{E}_B \end{bmatrix} \end{aligned} \quad (24)$$

Notice the transformation matrix looks very much like a matrix inverse. If the two measured Jones vectors, $E^{(1)}$ and $E^{(2)}$, have equal power, the transformation is a matrix inverse to a scale factor offset. As this matrix is a transformation from one space to another, this result should be intuitively pleasing.

C. Gain and Phase Imbalance

The transformation has the added benefit of compensating for gain and phase imbalance in the RF chain connected to the dual-port sinuous feed. Such imbalance would manifest as perturbations of γ and η in the measured Jones vectors and is eliminated when transformed to the reference polarization basis functions.

V. RESULTS

The transformation matrix above was applied to dual-pol data collected in two different CATRs, one in Atlanta, GA and the other in Asia. The sinuous feed described in Section II was used in each of the CATRs, dual-pol data collected using a polarization reference, and pre- and post-transformation co-pol and cross-pol results compared.

A. Atlanta Test Results

For the tests in Atlanta, an azimuth/elevation raster of data was collected over 1.7 to 2.6 GHz with the sinuous feed mounted as the AUT. As these data were collected in an az/el coordinate frame, they are subject to rotation of the polarization tilt for off-axis position values. In order to correct for this rotation, the data were transformed from az/el to Ludwig-3 polarization bases [11]. At this point, these data correspond to polarization states at different positions of the quiet zone if the sinuous feed were mounted as the CATR feed, while neglecting the effects of the reflector.

After converting to Ludwig-3, the broadside data point, which corresponds to the center of the quiet zone, was used to populate the transformation matrix in (21) at each frequency, and then applied to each sample point in the raster for that frequency. At broadside, for this test, the samples in the rotation matrix and the samples being rotated are the same, which leads to near-perfect correction, to machine precision.

Figure 6 shows the tilt angle vs. frequency for the H-port of the sinuous feed at broadside before correction as in Figure 2, now overlaid with the post-corrected tilt. Note the correction has virtually eliminated the tilt of the polarization ellipse at broadside.

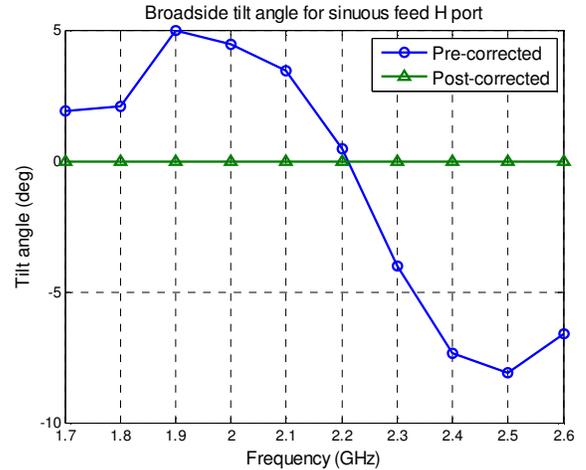


Figure 6. Pre- and post-corrected tilt angles vs frequency

Figure 7 shows pre- and post-corrected co-/cross-pol vs azimuth angle (-12 to 12 deg) when illuminated with a vertically polarized wave from the reference feed. This corresponds to a horizontal cut through the quiet zone if the sinuous feed were mounted as the CATR feed. Note the co-pol is at 0 dB allowing us to read off the cross-pol discrimination (XPD) from the H-pol curves. The pre-corrected XPD is around 21-22 dB for this particular frequency. Ignoring the broadside data point, the post-corrected XPD ranges from about 40 to 65 dB.

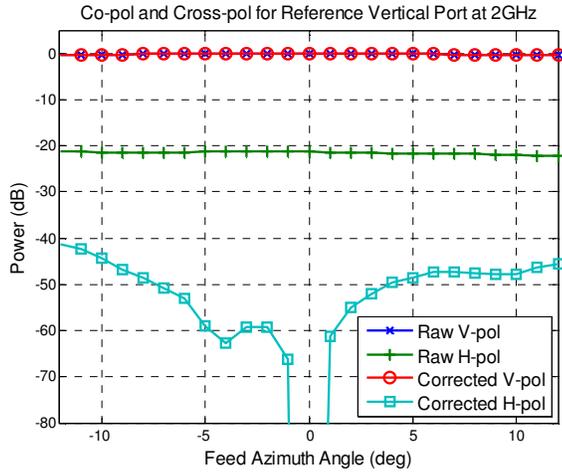


Figure 7. Pre- and post-corrected co/cross-pol at 2.0 GHz

B. Asia Test Results

In the Asian CATR, the sinuous feed was mounted as the CATR feed with a log periodic antenna as the polarization reference in the AUT position. Note that an SGH would be preferable, but for this test, no SGH was available. Using the log periodic, calibration data was collected over 0.7 to 4.0 GHz to populate the transformation matrix in (21). Then a separate dataset was collected on which the correction would be applied by rolling the sinuous feed through 360 degrees.

Figures 8-9 show the polarization responses vs roll angle for a single co-pol term at several frequencies across the band. Figure 8 shows the pre-corrected, raw data and Figure 9 shows the post-corrected patterns. These plots illustrate the movement of the nulls to $\pm 90^\circ$ as a result of tilt correction and a deepening of the nulls as a result of improved axial ratio.

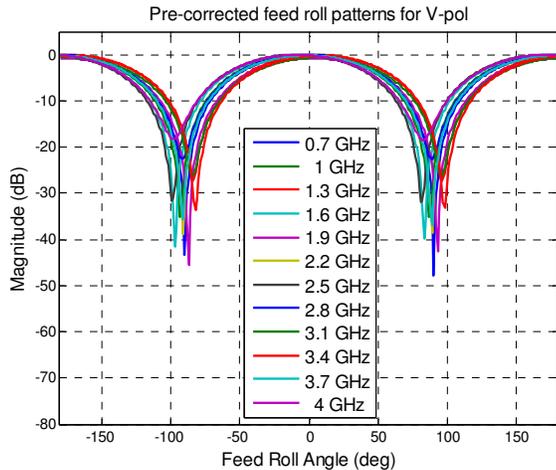


Figure 8. Pre-corrected co-pol vs roll angle at all frequencies

VI. CONCLUSION

A polarization correction has been derived and applied to a broadband CATR feed. The correction scheme enables the transformation from the broadband feed's polarization bases to a set of polarization bases of a more purely polarized reference antenna. The capability has been implemented and

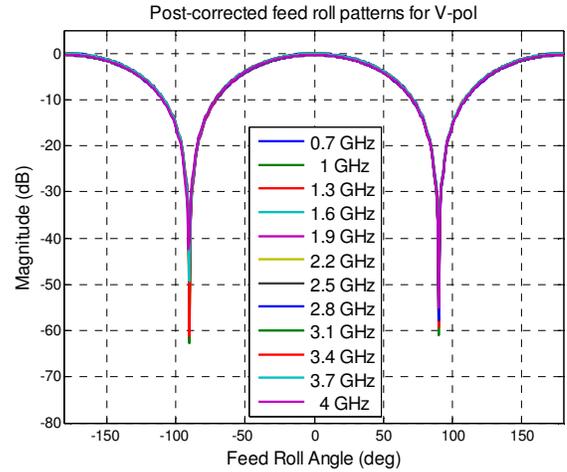


Figure 9. Post-corrected co-pol vs roll angle at all frequencies

tested in two CATRs and results validate the procedure's ability to improve cross-polarization and fidelity of the polarization state of the broadband feed.

ACKNOWLEDGMENT

The authors gratefully acknowledge Martin Mannion, Fernando Nelson, and John McKenna for their support in collecting data for this study.

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