CORRECTING DUAL PORT PROBE'S PORT-TO-PORT CALIBRATION USING NEAR-FIELD MEASUREMENTS

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Abstract

When a dual port probe is used for near-field measurements, the amplitude and phase difference between the two ports must be measured and applied to the probe correction files so that the measurements and calculations will have the same reference. For dual port linear probes, the measurement of this "Port-to-Port" ratio is usually accomplished during the gain or pattern measurements by using a rotating linear source antenna.[1]

When a dual port linear probe is used to measure a circularly polarized antenna, the uncertainty in this Port-to-Port ratio can have a significant effect on the determination of the cross polarized pattern. Uncertainties of tenths of a dB in amplitude or 1-3 degrees phase can cause changes in the cross polarized pattern of 5-10 dB.[2] [3] The paper will present a method for measuring the Port-to-Port ratio on the near-field range using a circularly polarized antenna as the AUT (Antenna Under Test). The AUT does not need to be perfectly polarized nor do we need to know its correct polarization. The measurements consist of two separate near-field scans. In the first measurement the probe is in its normal position and in the second it is rotated about the Z-axis by 90 degrees. A script then calculates the Port-to-Port ratio by comparing the cross-polarization results from the two measurements. Uncertainties in the Port-to-Port ratio can be reduced to hundredths of a dB in amplitude and tenths of a degree in phase. Measurements were taken at TRW's Large Horizontal Near-field Antenna Test Range.

Keywords: Antenna measurements; Circular polarization; Planar near-field; Probe Correction;

1.0 Probe Correction Equations for Dual Port Probes

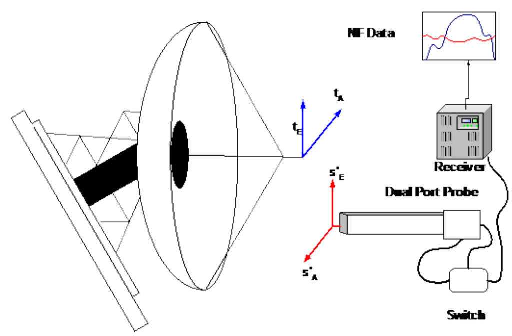

Figure 1 Schematic of near-field measurement with dual port probe.

A typical planar near-field measurement using a dual port probe is shown schematically in Figure 1. The probe is moved over a planar area that is usually very close to the AUT and at equally spaced points on a rectangular grid the receiver measures the amplitude and phase of the signal received by both ports of the probe. A switch is used to change from the X-polarized port to the Y-polarized port of the probe. This is done very fast so the measurements are made at essentially the same point. The port-to-port ratio is due to the difference in the electrical properties of the two paths from the space side of the probe to the common output connector on the switch. This ratio must be known so the measured data from the two ports will have a common amplitude and phase reference. The port-to-port ratio includes the electrical properties of the probe, the polarizer, connectors and cables, impedance mismatch between components and the switch.

The main and cross-component patterns of both the AUT and the probe have some effect on every measured data point in the near-field, and that effect is correctly accounted for in the two Equations describing the near-field measurements.

$$B_X(\vec{P}) = \int \left[t_A X_A + t_E X_E \right] e^{i\gamma d} e^{i\vec{K}\bullet\vec{P}} d\vec{K} \qquad (1)$$

$$B_Y(\vec{P}) = \int \left[t_A Y_A + t_E Y_E \right] e^{i\gamma d} e^{i\vec{K}\bullet\vec{P}} d\vec{K} \qquad (2)$$

In the above equations, B_X is the complex, amplitude and phase, data measured by the X-Port of the probe as a function of $\vec{P}$, where $\vec{P}$ is the x-y position vector defining the position of the probe in the near-field plane. $\vec{K} = k_x \vec{e}_x + k_y \vec{e}_y$ is the x-y part of the propagation vector that defines the direction of propagation of each plane-wave and γ is the z-component of the propagation vector. The symbols t_A and t_E represent the transmitting plane-wave spectra of the AUT, X_A and X_E are the receiving plane-wave spectra for the X-polarized probe, and Y_A and Y_E are the corresponding spectra for the Y-polarized probe. The subscript A denotes the Azimuth component of an AZ/EL spherical coordinate system which is the X-component along the principal axes, and E denotes the Elevation component which is the Y-component along the principal planes. In Equations (1) and (2) we have deleted the explicit reference that $t(\vec{K})$, $X(\vec{K})$ and $Y(\vec{K})$ are functions of $\vec{K}$ for brevity. It must be remembered that the near-field data, the spectral quantities and parameters such as the polarization ratios derived from them are functions of either $\vec{P}$ or $\vec{K}$ and are not constants.

The first step in the data processing is the calculation of the spectrum of the measured data using the Fourier transform.

$$D_X = t_A X_A + t_E X_E = \frac{e^{-i\gamma d}}{4\pi^2} \int B_X e^{-i\vec{K}\bullet\vec{P}} \, d\vec{P} \qquad (3)$$

$$D_Y = t_A Y_A + t_E Y_E = \frac{e^{-i\gamma d}}{4\pi^2} \int B_Y \, e^{-i\vec{K}\bullet\vec{P}} \, d\vec{P} \qquad (4)$$

Once the spectrum has been obtained, the transmitting spectra for the AUT are obtained by applying the probe correction.

$$t_A = \frac{\dfrac{D_X}{X_A} - \dfrac{D_Y}{Y_E \, \rho_X}}{1 - \dfrac{\rho_Y}{\rho_X}} \qquad (5)$$

$$t_E = \frac{\dfrac{D_Y}{Y_E} - \dfrac{D_X \, \rho_Y}{X_A}}{1 - \dfrac{\rho_Y}{\rho_X}} \qquad (6)$$

Where the probe polarization ratios are,

$$\rho_X = \frac{X_A}{X_E} \quad \text{and } |\rho_X| > 1 \text{ For X-Polarized Probe}$$

$$(7)$$

$$\rho_Y = \frac{Y_A}{Y_E} \quad \text{and } |\rho_Y| < 1 \text{ For Y-Polarized Probe}$$

Equations (5) and (6) are the full probe correction equations that are generally implemented in the software. For well-polarized probes with axial ratios on the order of 40 dB, the equations can be simplified, and for the following derivation we will neglect the cross-polarized terms in the probe correction. They will have a second order effect on the derived result. The term involving the ratio of polarization ratios in the denominators of (5) and (6) is extremely small compared to one and can be neglected. The second terms in the numerator of Equations (5) and (6) are due to the cross component coupling of the probe and will also be neglected. The simplified probe correction equations are then,

$$t_A \cong \frac{D_X}{X_A} \quad \text{and} \quad t_E \cong \frac{D_Y}{Y_E} \qquad (8)$$

For a circularly polarized antenna the linear components are combined to give the right and left hand circular components. For receivers and numerical calculations that use $e^{+j\omega t}$ for the time dependence of periodic variables, the right and left hand components are,

$$t_R = \frac{t_A + it_E}{\sqrt{2}} = \frac{\dfrac{D_X}{X_A} + i\dfrac{D_Y}{Y_E}}{\sqrt{2}} = \frac{D_X}{\sqrt{2}X_A}\left[1 + i\frac{D_Y X_A}{D_X Y_E}\right] \qquad (9)$$

$$t_L = \frac{t_A - it_E}{\sqrt{2}} = \frac{\dfrac{D_X}{X_A} - i\dfrac{D_Y}{Y_E}}{\sqrt{2}} = \frac{D_X}{\sqrt{2}X_A}\left[1 - i\frac{D_Y X_A}{D_X Y_E}\right] \qquad (10)$$

and the ratio of left to right components for the case where the main component is right hand circular is

$$\frac{t_L}{t_R} = \frac{1 - i\dfrac{D_Y X_A}{D_X Y_E}}{1 + i\dfrac{D_Y X_A}{D_X Y_E}} \cong \frac{1 - i\dfrac{D_Y X_A}{D_X Y_E}}{2} \tag{11}$$

The axial ratio and tilt angle are given in terms of the ratio by the equations

$$AR = \text{Axial Ratio} = \frac{1 + \left|\dfrac{t_L}{t_R}\right|}{1 - \left|\dfrac{t_L}{t_R}\right|}$$

(12)

$$\tau = \text{Tilt Angle} = \frac{\arg\left(\dfrac{t_R}{t_L}\right)}{2}$$

For a right hand circularly polarized AUT,

$$\left|\frac{t_L}{t_R}\right| \ll 1 \;\; and \;\; \frac{D_Y X_A}{D_X Y_E} \cong -i \tag{13}$$

and if the ratio of $\dfrac{X_A}{Y_E}$ is incorrect due to errors in the port-to-port ratio, there may be large errors in the polarization parameters of the AUT.

To represent the effect of such errors, we use Equation (8) to substitute for D_X and D_Y in Equation (11).

$$D_X = \mathbf{t}_A \mathbf{X}_A \;\; and \;\; D_Y = \mathbf{t}_E \mathbf{Y}_E \tag{14}$$

where the bold symbols represent the AUT and probe parameters without any error due to the port-to-port measurement. The measured data and the calculated spectra D_X and D_Y are defined by the true AUT and probe parameters not by any errors in the measured probe parameters. The probe errors only affect the results when the probe correction is applied. We also use the inverses of Equations (9) and (10) to represent the ratio of linear components in terms of the circular components also for the AUT parameters without probe errors.

$$\frac{\mathbf{t}_E}{\mathbf{t}_A} = \frac{-i\left(\mathbf{t}_R - \mathbf{t}_L\right)}{\mathbf{t}_R + \mathbf{t}_L} = \frac{-i\left[1 - \dfrac{\mathbf{t}_L}{\mathbf{t}_R}\right]}{1 + \dfrac{\mathbf{t}_L}{\mathbf{t}_R}} \cong -i\left[1 - 2\frac{\mathbf{t}_L}{\mathbf{t}_R}\right] \tag{15}$$

Using the fact that the magnitude of the ratio of the circular components is small and the phase is equal to twice the tilt angle,

$$\begin{aligned}\frac{\mathbf{t}_E}{\mathbf{t}_A} &\cong -i\left[1 - 2\frac{\mathbf{t}_L}{\mathbf{t}_R}\right] = -i\left[1 - 2\alpha e^{-i2\tau}\right] \\ &\cong -i\left(1 - 2\alpha\cos(2\tau) + i2\alpha\sin(2\tau)\right)\end{aligned} \tag{16}$$

a is the amplitude of the CP polarization ratio, is proportional to the axial ratio in dB, and or a perfectly polarized RHCP AUT, a=0. Using Equations (14) and (16), Equation (11) for the circular polarization ratio calculated using the measured probe parameters becomes

$$\begin{aligned}\frac{t_L}{t_R} &\cong \frac{1 - i\dfrac{D_Y X_A}{D_X Y_E}}{2} = \frac{1 - i\dfrac{\mathbf{t}_E X_A \mathbf{Y}_E}{\mathbf{t}_A \mathbf{X}_A Y_E}}{2} \\ &\cong \frac{1 - \left[1 - 2\alpha\cos(2\tau) + i2\alpha\sin(2\tau)\right]\left[\dfrac{X_A \mathbf{Y}_E}{\mathbf{X}_A Y_E}\right]}{2}\end{aligned} \tag{17}$$

The terms in the first brackets represent the influence of the AUT properties on the measured and calculated results and the terms in the second bracket represent the influence of the probe Port-to-Port ratio uncertainties on the results since they are the ratios of the true to the measured parameters. The probe ratio error will in general have both an amplitude and phase contribution and these can be represented by the term ε and δ.

$$\frac{X_A \mathbf{Y}_E}{\mathbf{X}_A Y_E} = \left(1 + \varepsilon\right)e^{i\delta} \cong 1 + \varepsilon + i\delta \tag{18}$$

ε and δ represent the errors in the measured port-to-port ratios and these are the parameters that we need to determine.

Combining Equations (17) and (18) and retaining first order terms gives for the ratio of Left to Right components for the measurement with the X-Probe aligned with the X-axis of the measurement system,

$$R(Pol=0)=\frac{t_L(0)}{t_R(0)}$$
$$\cong \alpha\cos(2\tau)-\frac{\varepsilon}{2}-i\left(\alpha\sin\left(2\tau\right)+\frac{\delta}{2}\right) \quad (19)$$

If the probe is now rotated about its axis by 90 degrees so the X-probe is now oriented along the Y-axis of the measurement system and new near-field data is measured and processed, the probe parameters are still the same, and the amplitude of the circular components of the AUT will also be unchanged. The tilt angle of the AUT will change by 90 degrees since the reference for the tilt angle is the location of the major axis of the X-polarized probe. The complex polarization ratio for this situation is then

$$R(Pol=90)=\frac{t_L(90)}{t_R(90)}$$
$$\cong \alpha\cos 2\left(\tau+90\right)-\frac{\varepsilon}{2}-i\left(\alpha\sin 2\left(\tau+90\right)+\frac{\delta}{2}\right) \quad (20)$$
$$=-\alpha\cos(2\tau)-\frac{\varepsilon}{2}-i\left(-\alpha\sin\left(2\tau\right)+\frac{\delta}{2}\right)$$

Adding the complex polarization ratios from the measurements at 0 and 90 degrees gives the desired result, an expression for the probe Port-to-Port errors,

$$R(Pol=0)+R(Pol=90)=-\varepsilon-i\delta \quad (21)$$

The real part of the sum is equal to the amplitude error and the imaginary part is equal to the phase error. The error may be calculated at each point of the far-field pattern, but the calculations will only be reliable in the regions where the assumptions used in deriving the final equation are valid. The two major assumptions are that the Left circular component is much smaller than the Right and that the probe errors are small. The first assumption is valid over most of the main beam, and so the equation should only be applied in this region. The final results will be improved by averaging all of the values calculated over the main beam. A weighted average is used where the weight is the ratio of main to cross component amplitude.

2.0 Measurement Example

Figure 2 shows the far-field main and cross component patterns that were obtained from a measurement with the

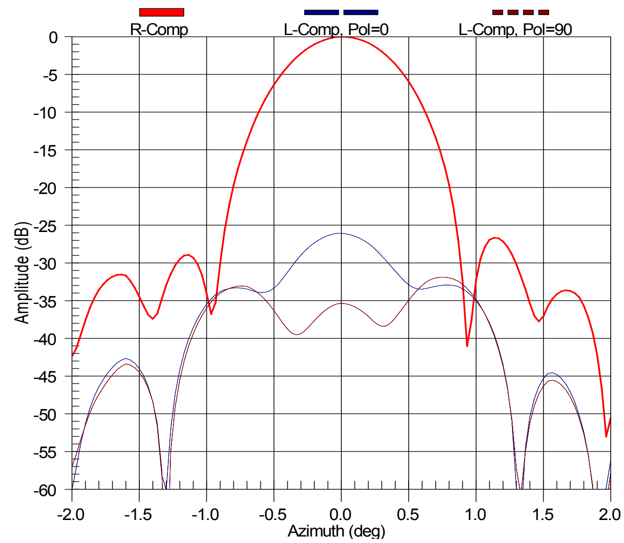

Figure 2 Main and Cross component far-field patterns before correction of probe Port-to-Port

probe at Pol = 0 orientation along with the cross component pattern from the Pol = 90 degree data. The nearly 10 dB difference between the two cross component patterns is an indication of the error in the probe Port-to-Port ratio. The circular polarization ratios were calculated using the two near-field data files and the amplitude and phase corrections were calculated for each point in the far-field pattern over the 4 X 4 degree region of the far-field using Equation (21). The resulting errors for the H-cut are shown in Figures 3 and 4.

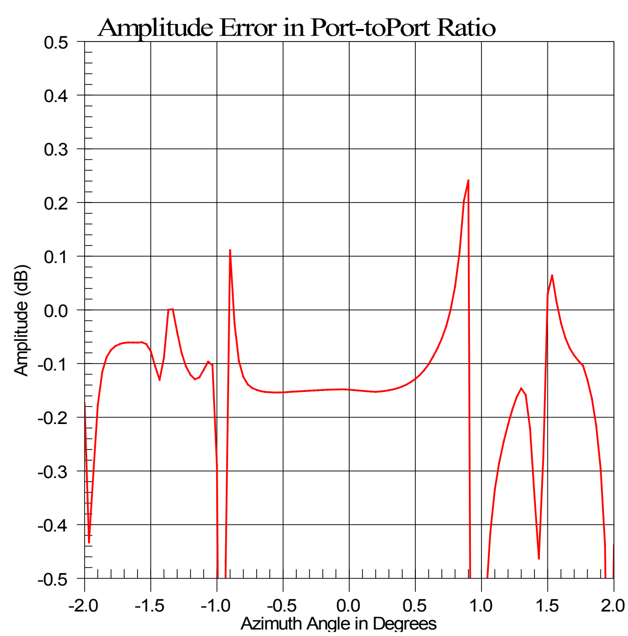

Figure 3 Amplitude error determined from using Equation (21) and near-field data at Pol = 0 and 90.

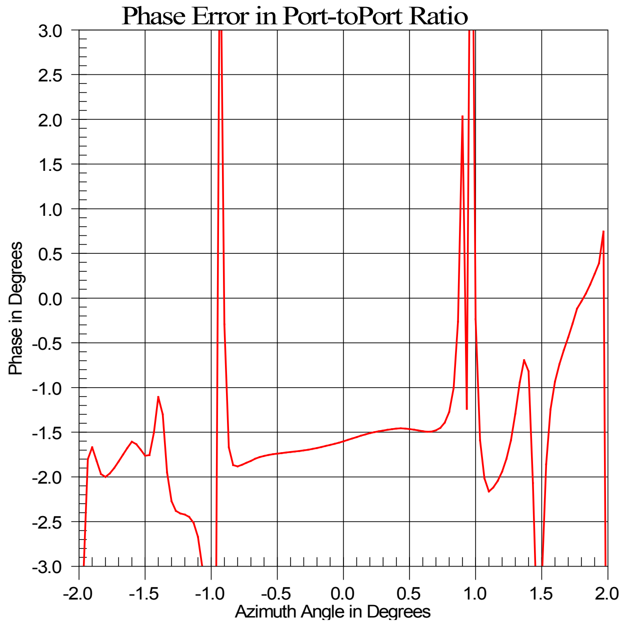

Figure 4 Phase error determined from using Equation (18) and near-field data at Pol = 0 and 90.

The weighted average was computed using all of the far-field data points and in this case gave a correction of 0.16 dB and 1.66 degrees. When these corrections were applied to the X-port of the probe and the far-field patterns recalculated, the resulting patterns for the same data files are shown in Figure 5. The cross component patterns now agree to within one dB or less over the full pattern.

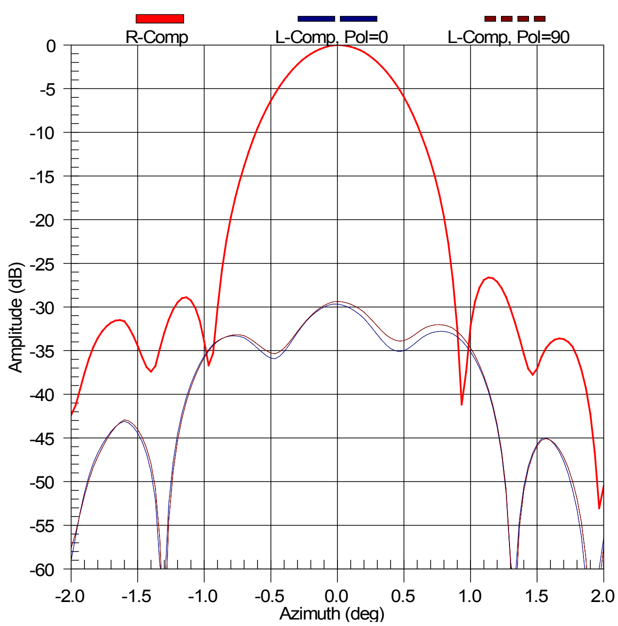

Figure 5 Main and Cross component patterns after correcting the Port-to-Port Ratio.

Running the correction program again after the first correction was applied resulted in a change in the amplitude of –0.02 dB and the phase of 0.02 degrees and a slight improvement in the agreement between the 0 and 90 degree data. This demonstrates that the process does converge to the correct answer.

3.0 Estimating Uncertainty of Measurement

The primary sources of uncertainty in the measurement and calculation are:

1. Amplitude and phase variation in the rotary joint used to rotate the probe.
2. Multiple reflections between the probe and the AUT and room scattering that may be different for the two orientations.
3. Differences in the amplitude and phase patterns of the two ports if the probe patterns are not rotated for the second set of data.
4. Leakage and crosstalk signals.
5. Drift in amplitude or phase between measurements.

The changes due to the rotary joint can be reduced or estimated if multiple data pairs are taken for both plus and minus 90 degrees rotations with different initial angles. A good rotary joint should have changes of less than 0.05 dB and 0.2 degrees.

The multiple reflections should be very similar for the two orientations, but can be estimated and reduced by taking repeat measurements at different Z-distances.

In the current implementation of the correction program the probe pattern is not rotated for the 90 degree data set. For the small angular region of the main beam and the broad probe patterns it is assumed that the azimuth and elevation patterns are identical. Comparing the pattern principal plane cuts showed that there is a slight difference in the phase patterns and this is the reason for the slope in the calculated phase correction shown in Figure 4. The maximum error is 0.3 degree and averaging over the main beam reduces this effect to less than 0.1 degree. Rotating the probe pattern for the rotated data could reduce this error.

Receiver leakage can affect the far-field cross polarized pattern in the on-axis region if it is large enough. Methods are available to measure and subtract the leakage signal before processing to the far-field if necessary.[4] In the current measurement this was not necessary because the leakage was approximately 85 dB below the peak near-field amplitude and 65 dB below the peak far-field amplitude.

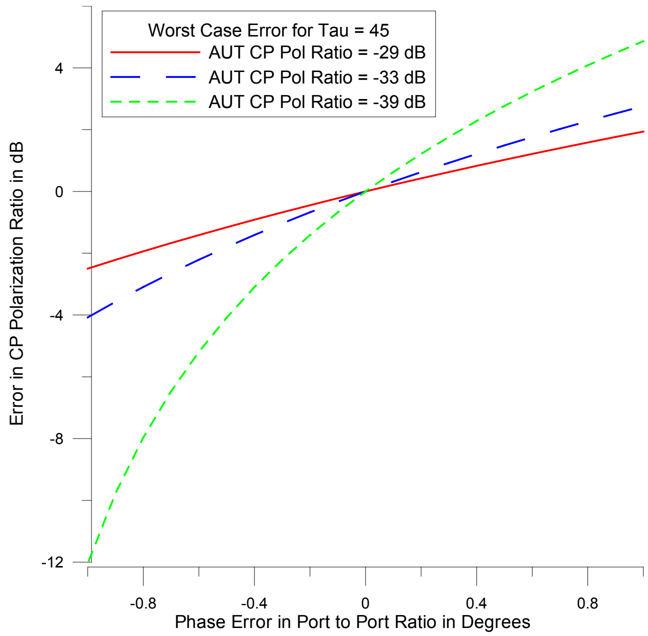

Figure 6 Error in CP polarization ratio due to amplitude error in probe port-to-port ratio.

Drift correction techniques[5] can be used to reduce this error if necessary by periodically measuring one or more reference points during the near-field measurement. With this correction, the effective drift from the beginning of the 0 degrees scan to the end of the 90 degree scan can be on the order of 0.04 dB and 0.2 degrees.

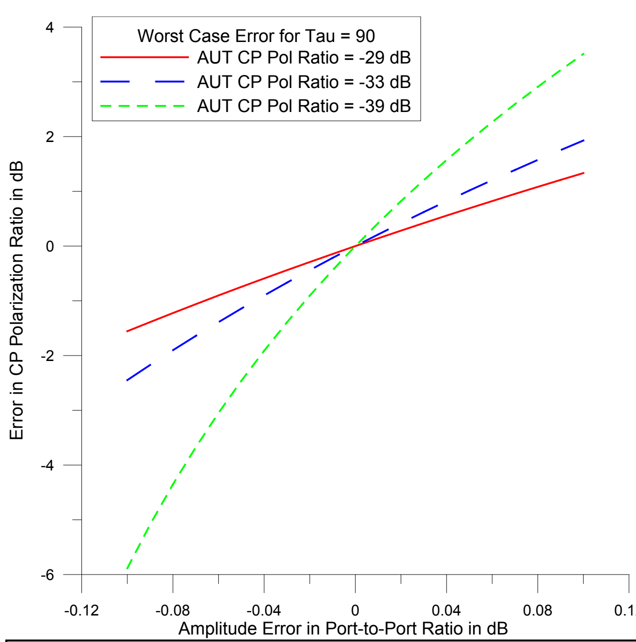

Figure 7 Error in CP polarization ratio due to phase error in probe port-to-port ratio.

Figures 6 and 7 show worst case curves for the error in the AUT polarization ratio amplitude as a function of the error in the port-to-port ratio amplitude and phase. The actual error will also depend on the tilt angle of the AUT and these curves have been calculated for the worst case situation for each quantity. As seen from Equation (19) the sensitivity to amplitude errors is very small when t=45 degrees and the sensitivity to phase errors is small when t=0.

4.0 Conclusions

A technique has been developed and tests for either measuring or checking the calibration of the port-to-port ratio for a dual port linear probe. The measurement is performed using the actual CP antenna that will be measured by the probe. This approach has the advantage of testing the complete probe and associated cables and switch at the time of use and so errors in the original calibration or changes in components can be measured and correctly adjusted. Using this calibration technique, good cross-polarized results on circular polarized antennas can be obtained while using dual port liner probes.

5.0 Acknowledgements

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6.0 References

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