

Identifying Pointing Errors for the NIST 18 Term Error Technique

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ABSTRACT

The NIST 18 Term Error Analysis Technique uses a combination of mathematical analysis, computer simulation and near-field measurements to estimate the uncertainty for near-field range results on a given antenna and frequency range. A subset of these error terms is considered for alignment accuracy of an antenna's RF main beam. Of the 18 terms, several have no applicable influence on determining the beam pointing or the terms have a minor effect and when an RSS estimate is performed they are rendered inconsequential. The remainder become the dominant terms for identifying the alignment accuracy. There are six terms that can be evaluated to determine the main beam pointing uncertainty of an antenna with respect to dual band performance. Analysis of the near-field measurements is performed to identify the alignment uncertainty of the main beam with respect to a specified mechanical position as well as to the main beam of the second band.

Keywords: Antenna Measurements, Error Analysis, Near-Field Measurements, Antenna Pointing

1.0 Introduction

This paper describes the need to identify far-field beam pointing of an antenna measured in the near-field. This need to identify the far-field electrical boresight was inspired by the requirement to accurately define the position of two beams from the same antenna in a dual frequency band antenna system. In order to accurately characterize the far-field electrical boresight location one must understand the errors and limitations of the measurement method. The NIST 18 Term Error Analysis Technique [1] has become an industry standard for evaluating near-field antenna measurement facilities. This paper will discuss which of the traditional 18-term errors have a direct impact on the accuracy of the far-field electrical boresight. The electrical boresight estimation is identified by using both an absolute and relative method as well as looking at the beam pointed at boresight (0 degrees) and steered to 45 degrees. The measured data

and scanner performance is based on previously presented results [2].

	Error Source	Primary
		Evaluation Method
1	Probe relative pattern	Analysis
2	Probe polarization ratio	Analysis
3	Probe gain measurement	Analysis
4	Probe alignment error	Analysis
5	Normalization constant	Analysis
6	Impedance mismatch	Analysis
7	AUT alignment error	Analysis
8	Data point spacing	Measurement
9	Meas. area truncation	Measurement
10	Probe x, y-position errors	Analysis
11	Probe z-position errors	Analysis
12	Multiple reflections (probe/AUT)	Measurement
13	Receiver amplitude nonlinearity	Measurement
14	System phase error due to:	
	Flexing cables/rotary joints	Measurement
	Temperature effects	Measurement
	Receiver phase errors	Simulation
15	Receiver dynamic range	Measurement
16	Room scattering	Measurement
17	Leakage and crosstalk	Measurement
18	Random errors in amplitude/phase	Measurement

Table 1 – Summary of the NIST 18 Term Error Model

2.0 Estimating Uncertainties for Main Beam Pointing

The final result of a planar near-field measurement, a far-field pattern as a function of angle, describes both amplitude and phase for each component of the field in each direction. The measurement of interest here is a single pair of angular coordinates that describe the main lobe direction of the antenna pattern. This set of coordinates may be computed from the far-field pattern in a number of ways. For tracking (“difference”) beams (beams with a null in the desired direction) the pointing direction is typically the direction at which a local signal-strength minimum occurs. For communications (“sum”) beams, two common methods are: 1) simply noting the location of the highest amplitude measurement, or 2) taking the coordinates of the centroid of the area above a certain level on the pattern’s contour-map representation. In this analysis, we consider the alignment of sum beams, and have used the first computing method. The second method may be used to further reduce uncertainties in the reported values, as it is less sensitive to small pattern variations that may appear at the beam peak but have no effect on the coverage area of the main beam. When considering the question of alignment accuracy, it is important to define what the alignment reference will be. In this paper, our estimates of alignment uncertainty are done in two modes. The first (“Absolute”) assumes that “alignment” is defined as the relationship between the electrical beam direction and the mechanical interface to the antenna. The second (“Relative”) assumes that we are concerned only with the relationship between two co-aligned beams (TX and RX) produced by the AUT, when the AUT is tested without removing or remounting. This method allows for a more accurate estimate of the two-beam relationship, as the largest sources of alignment error are common to both beams and thus self-cancelling. Of the 18 terms typically considered in the near field range error budget, many have practically no effect on the determination of beam pointing. Others have relatively minor effect, and in the RSS estimation of the total error are still completely dominated by the major factors considered here. The dominant terms, which are considered in this paper, are as follows:

Term 7a – AUT Alignment Error (Uncertainty in defining range coordinates)

Term 7b – AUT Alignment Error (Uncertainty in alignment to range coordinates)

Term 10 – Probe X, Y Position Error

Term 11 – Probe Z Position Error

Term 12 – Mutual Coupling

Term 14 – Systematic Phase Error

Term 18 – Random/Repeatability Errors

2.1 Term 7a – AUT Alignment Error (Range Coordinates)

The AUT Alignment error term has been divided into two segments for the purposes of this analysis. The first segment involves the determination of the range coordinate system to which the AUT will be aligned. In a planar near field scanner system, the measurement coordinate system is defined by the scan plane – more specifically, the “boresight” direction of the range is defined as a vector perpendicular to the best-fit plane described by the probe as it moves over the X/Y scan area for the measurement. Uncertainty in knowing the best-fit plane translates into uncertainty in the boresight vector, and contributes to error in the reported main beam pointing coordinates.

In the case of the planar scanner system used for this experiment, the scan plane is determined using a calibrated “plane laser” and sensor during scanner mechanical calibration. By measuring the Z position of the probe at a regular grid of commanded positions, a set of correction values is generated that is then used in the scanner control software to reduce the positional errors. With this correction activated, the plane laser is again used to produce a record of the errors between commanded and actual probe Z-positions. A plane is fit to the final set of data – this plane defines the boresight vector. Because the plane laser has a finite measurement uncertainty, there is always some error in knowing the probe’s actual location relative to the best fit plane at any particular commanded position. The plane laser is used to determine the planarity of the PNF scanner used in this experiment and an “uncertainty grid” is defined. The actual accuracy of these measurements made with the plane laser and sensor is less than 0.001 inches.

In order to align the AUT to the range coordinates, a touch probe is used to measure the distance from the scanner’s probe carriage to machined mounting points on the AUT mount. As this alignment depends on the scanner itself, errors between the actual probe positions and the best fit plane are in essence errors in determining the range coordinate system. The accuracy of this determination will depend on the x-y position of the X-Y reference points with respect to the scanner. Assuming worst-case points on the best fit corrected grid, in a 24-inch span there could be a -0.63 mil error on one side and a +1.23 mil error on the other. Scaled to the 10-inch AUT mount point spacing, this worst-case error becomes 0.8 mils across the AUT mount points. Adding a 1-mil uncertainty between two laser Z-measurements, the total error could be as much as 0.0018 inches over the 10-inch span. This linear error results in an angular error of up to 0.010 degrees in the definition of the “boresight” vector. Note that this error does not apply to our second mode (“Relative”) of defining alignment, as the range coordinate system is common to both measurements.

2.2 Term 7b – AUT Alignment Error (Aligning to Range)

This error term deals with AUT azimuth and elevation mounting errors. As with Term 7a above, these errors do not affect the pattern directly but do affect the mechanical-to-electrical alignment of that pattern to the range coordinate system, and thus contribute to errors in the reported main beam pointing coordinates. As previously mentioned on our scanner, a touch probe (Starrett Dial Indicator Model 81-231) is used to measure the distance from the scanner's probe carriage to machined mounting points on the AUT mount. This alignment procedure requires that the Z-distances to each of the four AUT mount points be less than 2 mils from one another. As the particular dial indicator used has a repeatability and accuracy more than adequate to measure within this 2-mil range, we take the total error to be essentially 0.002 inches. The corresponding angular error for this term is thus 0.011 degrees. Again, this particular error does not apply to the "Relative" mode of defining alignment, as the alignment is common to both measurements. If a more accurate range is used initially, the observed errors would be improved.

2.3 Term 10 – Probe X and Y Position Errors

Errors in the probe's X or Y position affect the AUT's far-field pattern, gain and polarization. The theoretical treatment for X-Y errors in planar measurements can be used to estimate these errors. For the case where the main beam is approximately normal to the X-Y plane, the errors in gain and sidelobe are,

$$\Delta G_{dB}(\theta, \phi) \leq \frac{8.7 \Delta_{xy} (RMS)}{\eta L} g(\theta, \phi)$$

[Main Beam]

$$\Delta P_{dB}(\theta, \phi) \leq \frac{4.3 \Delta_{xy}(\theta, \phi)}{L} g(\theta, \phi)$$

[Sidelobes]

where G is the antenna gain, P the relative pattern L the antenna major dimension, η the aperture efficiency, and Δ_{xy} the position error. $g(\theta, \phi)$ is the reciprocal of the sidelobe level in voltage not dB, for instance, for a -40 dB sidelobe, $g(\theta, \phi)$ is 100.

The x or y position error amplitude Δ_{xy} , is obtained from the calibration of the x and y-position encoders and the measurement of the rail straightness. This was done with a laser tracker instrument that measured the deviation in x,y and z over the full area of the scanner. Only the position errors within the area used for these measurements will produce errors in the far-field results

and so the values identified are for that limited region of the scanner. The RMS value is used for the peak gain directions. For the sidelobe regions $\Delta_{xy}(\theta, \phi)$ is the magnitude of a periodic position error with the period that will affect one particular direction off-axis identified by the angles (θ, ϕ) . This can be found from a Fourier analysis of the position errors as a function of x and y if measurements are made at small enough increments to resolve all periodic components. This was not required for these measurements since the position errors were very small within the scan region.

Since the far-field pointing is directly related to the phase slope in the near-field data, a scale error in either X or Y will have the major effect on the electrical boresight. There will be no error for a beam along the Z-axis since there is no phase slope. For a beam steered 45 degrees off boresight, the error can be estimated as follows: Assume a near-field data set having a "hot zone" (area with strong signal) approximately 12 inches across. If the actual endpoints for a "12-inch" move were both off, in opposite directions, by 0.6 mil, the computed beam angle would be 44.994 degrees, for an error of +/-0.006 degrees. This error will be partially self-cancelling for the "relative" mode of beam alignment. We've kept the full value, for a relatively pessimistic estimate of this term.

2.4 Term 11 – Probe Z Errors

This term is included here for completeness, but has already been considered in the analysis of terms 7a and 7b. Probe Z-errors only affect the measured beam pointing to the extent that they vary linearly over the surface of the scan plane. The "random" component of the Z-errors over the scan surface (as well as the "even-term" components) will affect measured beam width, but will not change the beam direction. No table entries have been generated for Term 11, since they are incorporated in the earlier terms.

2.5 Term 12 – Mutual Coupling (Probe/AUT)

The presence of multiple reflections between the probe and AUT are identified by comparing patterns from different probe-to-antenna separation distances. This works well when the repeatability between scans is good as it was for these measurements. Generally scans are taken at four or five intervals spaced $\lambda/8$ apart. For the purpose of estimating angular pointing error due to this error source, the Beam Peak locations reported by the measurement software for each of five of these scans were compared. Mutual coupling is typically only noticeable when the AUT and probe are pointed directly at one another. For the case of the 45-degree beam, the uncertainty has been reduced to one third the value gathered from the mutual coupling test data which was done with the AUT pointed at boresight. As this error depends on the individual characteristics of the each beam

tested, it applies twice to the case of aligning beam-to-beam on the same antenna. We have taken the RSS sum of the two errors in this case.

2.6 Term 14 – Systematic Phase Error

Systematic phase errors are errors in the receiving system. Random phase errors are excluded from this set of errors and have their own line item (Item 18). Among the errors included in this set are cable flexing, rotary joints and temperature effects, with the dominant source being the measurement cable flexing. To determine the value for this error term, single X and Y cuts are made with the AUT-Probe path bypassed with a semi-rigid cable. The cable is supported in such a manner to have minimum bending during the scan. This produces a nearly constant amplitude and phase near-field data set that represents the changes in amplitude and phase due to the measurement cable flexing. A normal 2D measured data set is then modified by adding the loopback cable measurements to the original amplitude and phase. Comparing the far-field patterns with and without the cable errors gives an estimate of the uncertainty due to this source. Figure 1 shows the measured amplitude and phase variation in the X-direction which had the larger change. The primary result of the nearly linear cable phase change will be a shift in the azimuth boresight of 0.004 degrees at the receive frequency over the full scan plane. For a 12 to 24-inch near-field “hot spot,” this error could be as high as 0.007 degrees if the measurement is done in the worst possible spot in the cable travel. In general, this term applies to beams pointed at any angle. It applies essentially equally to both beams, and should be partially self-cancelling in the case of beam-to-beam alignment. We’ve again used a pessimistic estimate of the full error value for this case.

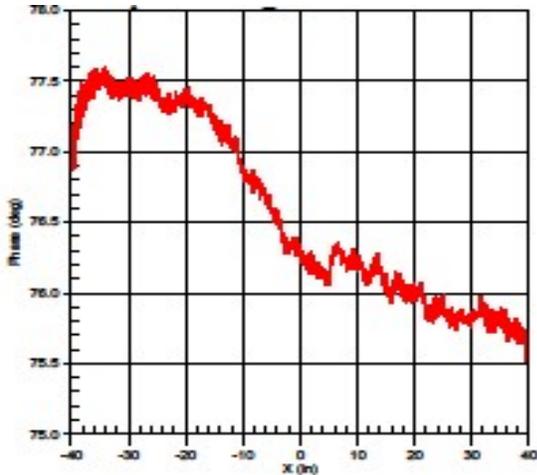


Figure 1 – Phase variation due to X-cable measured with a loop-back cable

2.7 Term 18 – Random Amplitude/Phase Errors

This set of errors is a combination of all non-repeatable errors due to the receiver, cables, temperature, leakage, AUT variations etc. The most direct way of identifying this quantity is to compare the far-field output of two or more scans taken with the exact same scan parameters. The assumption made here is that the repeatability is at least as good as this data shows, since repeatability errors are naturally included in this data. For the “absolute” alignment case, the effect of “double booking” the repeatability and mutual coupling errors is minimal because of the nature of the RSS summation of errors. This double booking is admittedly pessimistic in the “Relative” alignment case, as the Mutual Coupling and Random Errors terms are the major contributors. Since the effect of these errors does not depend on beam pointing angle, the uncertainty for a 45-degree beam was not reduced as it was in estimating the Mutual Coupling term. As with several of the other terms, the RSS sum of two equal-magnitude errors was used for this term in computing the “Relative” beam alignment uncertainty.

2.8 Combination of Uncertainties

Tables 2 and 3 summarize the results of the individual error sources for beam pointing. The overall error in the far-field beam peak is also computed.

Error Source	TX or RX Band	
	Uncertainty 0°	Uncertainty 45°
7a - Defining Range Coordinates	0.010	0.010
7b - AUT Alignment Error	0.011	0.011
10 - Probe X and Y Position Error	0	0.006
12 - Mutual Coupling	0.006	0.002
14 - Systematic Phase Error	0.007	0.007
18 - Random Amplitude and Phase Errors	0.006	0.006
Total (RSS)	0.018	0.019

Table 2 – Estimated Uncertainties for Beam Pointing – Absolute

Error Source	TX to RX Band	
	Uncertainty 0°	Uncertainty 45°
7a - Defining Range Coordinates	0	0
7b - AUT Alignment Error	0	0
10 - Probe X and Y Position Error	0	0.006
12 - Mutual Coupling	0.008	0.003
14 - Systematic Phase Error	0.007	0.007
18 - Random Amplitude and Phase Errors	0.008	0.008
Total (RSS)	0.013	0.013

Table 3 – Estimated Uncertainties for Beam Pointing - Relative

3.0 Summary

This paper describes the need to identify far-field beam pointing of an antenna measured in the near-field. The NIST 18 Term Error Analysis is used and the primary contributing errors for beam misalignment are presented. For an antenna measured on a planar near-field scanner, the error values are determined and characterized for the cases where the beam is pointed at boresight or 0° and steered to 45° . The absolute error of the antenna main beam aligned to the mechanical system of the scanner and mounting bracket is compared to the relative error of two different frequency bands radiating in the same aperture and their co-alignment. The error due to the definition of range coordinates may be improved by using a more precise measurement technique to characterize the scanner probe position. Reduction of AUT alignment error may be implemented by reducing the allowable tolerances between the dial indicator readings. Probe position errors are not easily improved without major adjustment and improvements to the measurement scanner. Errors due to mutual coupling may be improved by analyzing the reported beampeak locations using the discussed "centroid" method instead of simply identifying the greatest amplitude in the antenna pattern. Phase errors due largely to cable flexing during a measurement may be improved by using new cables or a cable type that is extremely phase stable with flexure and over temperature swings. K-correction removing repeatable portions of the cable flexure, resulting in phase changes, may also be used. Random errors in amplitude and phase can best be reduced by improving temperature stability in the scanner environment, changing cables and cable routing, and implementing an improved method of locating the beampeak in the far-field that is not sensitive to small ripple or noise.

4.0 REFERENCES

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5.0 ACKNOWLEDGMENTS

The authors wish to thank ThinKom Solutions, Inc. for the use of the array antenna used in these measurements and the L-3 Communications, CS-W for the support and cooperation in the use of their near-field measurement facility.