Application of Spherical Near-Field Uncertainty Analysis to Positioner Design

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***Abstract*—Several methods have been proposed to identify potential sources of Spherical Near-Field measurement uncertainties, including simulated, empirical, and analytical studies. One of the goals of such work is to understand the degree to which the measured results of a given system should be trusted. Another important benefit can be obtained by applying uncertainty analysis during system design to achieve better performance in the realized system.**

This paper shows how a Roll over Azimuth positioning system was analyzed to determine the major mechanical contributors to uncertainty in a W-band Spherical Near-Field system. The results of the analysis were used to target specific improvements to components of the positioning system. These changes resulted in better measurements at minimal incremental cost, yet without resorting to the expense of high accuracy position feedback. The relationship between the primary mechanical sources of uncertainty and the quality of the Spherical Near-Field measurement is described. This example illustrates the detailed work behind uncertainty analysis and shows its value in making appropriate design decisions.

***Index Terms*—spherical near-field, uncertainty, positioner.**

I. INTRODUCTION

Spherical Near-Field (SNF) measurement systems require that the antenna under test be probed along a spherical surface. Various mechanical positioning configurations have been used to implement spherical probing, including Roll over Azimuth, Gantry over Turntable, and Arch over Turntable. In this paper, a Roll over Azimuth configuration is examined for a measurement system that will operate in X, Ka, and W bands.

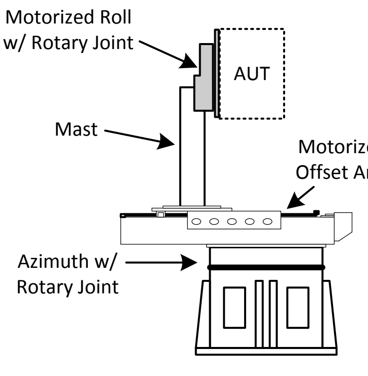

Figure 1 Roll over Azimuth Positioner Evaluated

Before this project, the existing practice for SNF systems that operate above 40 GHz was to incorporate positioners with high accuracy position readout sensors. However, in this case, the extra expense was high enough that an uncertainty analysis was undertaken to determine whether the large expense was actually required.

The uncertainty analysis was largely based on [1] and consultation with its author. The technique described therein uses the concept of a quality factor, which is defined as the fraction of a wavelength that is allowed as uncertainty. This is applied to create an error budget for Theta, Phi, and Radius. Analysis of mechanical uncertainties in this particular Roll over Azimuth configuration is performed with the results compared to the error budget.

The choice of quality factor for this system was a judgment call – there were no specifications for system performance nor positioning system accuracy. In general, adequate measurement results would be expected for a quality factor of 10, and excellent results would be expected for a quality factor of 50-100. A design goal was set for this positioning system to have a quality factor of 20, which was expected to give very good results.

II. UNCERTAINTY ANALYSIS STEPS

Based on a minimum sphere equal to the antenna diameter (D_{min}) along with the maximum frequency of operation, the spacing of grid points along both the Theta and Phi axes can be determined [1]. The free space wavelength at the frequency of interest is represented by lambda (λ).

$$\text{Grid Spacing} <= \lambda / D_{min} \text{ radians} \quad (1)$$

Dividing the grid point spacing by the quality factor (F_Q), an error budget was established for Theta and Phi.

$$\text{Theta, Phi error} <= \text{Grid Spacing}/F_Q \quad (2)$$

Since any change in the radius between the antenna under test and the probe causes a change in the measured phase, radial uncertainty would also impact measurement accuracy. Dividing lambda at the maximum frequency of operation by the quality factor, an error budget was established for radial uncertainty.

$$\text{Radial error} <= \lambda / F_Q \quad (3)$$

With error budgets established for Theta, Phi, and Radius, the positioning system could be evaluated and compared to this standard. Initially the primary concern was to determine the uncertainty in Radius due to bearing imperfections in the Azimuth and Roll positioners. The term wobble is used to describe the angular deviation in an axis as illustrated in Figure

2. The wobble results in nutated motion of the antenna under test (AUT) along the radial dimension of the test range.

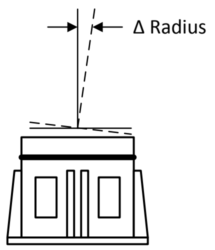

Figure 2 Radius Error due to Azimuth Axis Wobble

Uncertainty regarding the pointing angle of the test antenna in the Theta dimension is primarily determined by the readout error of the Azimuth axis. However, wobble in both the Roll and Azimuth axes can also cause additional uncertainty. The root sum squared (RSS) of these three parameters is used as a comparison to the Theta error budget.

Similarly, uncertainty of the pointing angle of the test antenna in the Phi dimension is primarily determined by the readout error of the Roll axis, but it is exacerbated by wobble in both axes. The root sum squared (RSS) of these three parameters is used as a comparison to the Phi error budget.

The Radial uncertainty is also affected by wobble in both the Azimuth and Roll axes, but is further affected by bearing radial runout which can result in axis translation along the radial dimension. In the case of Azimuth axis wobble, Radial uncertainty is multiplied by the height of the Roll axis above the Azimuth bearing divided by the Azimuth bearing radius. The root sum squared of these three parameters is used as a comparison to the Radial error budget:

- Delta radius due to Azimuth axis wobble
- Delta radius due to Roll axis wobble
- Azimuth axis translation along the radial dimension.

III. Uncertainty Calculations

An assessment of Theta, Phi, and Radial uncertainty was performed for two frequency bands, each with a different maximum antenna size. At W-band, the maximum antenna size was 6 inches, while at Ka-band, the antenna could be as large as 10 inches.

A spreadsheet was created to analyze baseline performance using existing standard positioners. The spreadsheet was subsequently used to evaluate potential performance improvements. Initial analysis showed that the standard positioner specifications were sufficient to provide a quality factor of >20 for a 10 inch antenna at 40 GHz. However, the system would only provide a quality factor of 8.7 for a 6 inch antenna at 110 GHz.

Analysis revealed that the Azimuth axis wobble was the primary contributor to larger uncertainty than desired. The magnitude of the wobble is determined by the bearing axial runout, bearing compliance, bearing radius, and height of the Roll axis above the Azimuth axis. By using a higher class of bearing and adding preload, the axial runout and bearing compliance could be improved significantly with minimal effort and cost. The remainder of the existing mechanical design could be preserved, and the desired performance could be met. Expensive, high accuracy position readout sensors would not be required.

Azimuth axial runout was improved from 0.002 inches to 0.0008 inches and bearing compliance was improved from 0.0086 inches to 0.0046 inches. Analysis showed that the electrical phase uncertainty at 110 GHz due to radial motion was reduced from 41.5 electrical degrees to 18.5 electrical degrees, resulting in a quality factor of 19.5, very close to our selected design goal.

An example of the spreadsheet with the parameters for the final design at 110 GHz is shown at the end of this paper in Table 1. Note that the Roll axis construction employs 2 bearings that are mechanically connected by a 6” tube. The calculation for “Angular deviation from normal” (wobble) is based on this configuration. The Azimuth axis consists of a single bearing that is 14” in diameter. Its wobble is the sum of “Angular deviation from normal” plus “Angular deviation due to compliance”.

IV. Results

The positioning system with the better bearing was built and installed with the measurement system. Measurements were made at 94 GHz using a standard gain horn of maximum dimension 2.5 inches. Uncertainty calculations were repeated using this test condition, resulting in a slightly better quality factor of 22.9, or 0.044λ for radial uncertainty. Very good results were obtained as documented in [2].

V. Conclusions

Because of the complexity of performing uncertainty analysis and determining the impact of various sources of error on any given measurement, rules of thumb are sometimes used as a guide for system design, resulting in an overly conservative approach and excess costs. Ideally, one would be able to use detailed analysis of error sources for a positioning system, combined with other non-mechanical sources of error, to predict system level performance and make design decisions. The impact of specific sources of mechanical error on the calculated far-field pattern has been the subject of recent research [3]. Further work could potentially result in better tools for system design.

Meanwhile, the concept of quality factor can be a useful tool for making design tradeoffs by providing a figure of merit for comparing one solution to another. And choosing a reasonable factor does result in a viable measurement system. By applying the quality factor concept to positioner design, more intelligent design decisions have been made with sound results. In this case, the large expense of high accuracy positioner axes was avoided, and instead the minimal cost of a higher class bearing was incurred with very good measurement results.

VI. References

[1] Doren W. Hess, "An Expanded Approach to Spherical Near-Field Uncertainty Analysis", Proceedings of the Antenna Measurement Techniques Association, 2002.

[2] Doren W. Hess, John McKenna, and Steve Nichols, "A Composite Near-Field Scanning Antenna Range for Millimeter Wave Bands", Proceedings of the Antenna Measurement Techniques Association, 2004.

[3] Michael H. Francis, "Estimation of Far-Field Errors Due To Mechanical Errors In Spherical Near-Field Scanning", Proceedings of the Antenna Measurement Techniques Association, 2012.

Table 1 Uncertainty Calculations for Final Design at 110 GHz

Antenna Calculator						
AUT Diameter =	6	inches		Electrical Size	56	lambda
Max Frequency =	110	GHz		Wavelength	0.107	inches
Quality Factor =	20			QF as percent	5.0%	
				Far field	55.9	feet
				Beamwidth	1.31	degrees
Spherical Near-Field Parameters						
Minimum Record Increment	1.025	degrees	(Nyquist interval for transformation to far-field)			
Angle Error Budget	0.051	degrees	(Theta & Phi errors each should not exceed)			
Radius Error Budget	0.0054	inches	(Changes in R primarily impact phase measureme			
Test Positioner	(6111 Roll axis over 51152 Azimuth)					
Roll axis						
Position Readout Error	0.05	degrees				
Radial runout, bearing 1	0.0004	inches				
Radial runout, bearing 2	0.0005	inches				
Distance between bearings	6	inches				
RSS of 2 runout specs	0.00064	inches				
Angular deviation from normal	0.0061	degrees				
Azimuth axis						
Position Readout Error	0.03	degrees				
Radial runout	0.0007	inches	***Class 4 bearing w/5/10 preload***			
Axial runout	0.0008	inches	***Class 4 bearing w/5/10 preload***			
Bearing radius	7	inches				
Angular deviation from normal	0.0065	degrees				
Angular deviation due to compliance	0.0046	degrees	***Class 4 bearing w/5/10 preload***			
Height of roll axis above azimuth	28	inches				
Z-axis motion due to angular deviation	0.00545	inches				
Theta						
Position Readout Error	0.03	degrees				
Roll Axis wobble	0.0061	degrees				
Azimuth Axis wobble	0.00655	degrees				
Theta Error	0.031	degrees	(RSS of above 3 parameters)			
Theta Error Margin	0.020	degrees				
Phi						
Position Readout Error	0.05	degrees				
Roll Axis wobble	0.0061	degrees				
Azimuth Axis wobble	0.00655	degrees				
Phi Error	0.051	degrees	(RSS of above 3 parameters)			
Phi Error Margin	0.000	degrees				
Radius						
Deviation due to Azimuth Axis wobble	0.0054	inches				
Azimuth Axis translation	0.0007	inches				
Deviation due to Roll axis wobble	0.0003	inches				
Radius Error	0.0055	inches	(RSS of above 3 parameters)			
Phase Error due to Radius Error	18.45	electrical degrees		**19.5**		
Radius Error Margin	(0.0001)	inches				