\An Expanded Approach to Spherical Near-Field Uncertainty Analysis

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We at MI Technologies have employed the Hansen error analysis [1] developed at the Technical University of Denmark (TUD), as a starting point for new system layouts. Here I expand it in two ways: the approach to mechanical errors, and the approach to system design.

I offer an alternative approach to the analysis of mechanical uncertainties. This alternative approach is based upon an earlier treatment of spherical coordinate positioning analysis for far-field ranges [2]. The result is an appropriate extension of the TUD uncertainty analysis.

Also, the TUD error analysis restricts its attention to three categories of errors: mechanical inaccuracies and receiver inaccuracies and truncation effects. An error analysis for a spherical measurement system should desirably contain entries equivalent to the 18-term NIST table for planar near-field [5]. In this paper, I offer such an extended tabulation for spherical measurements.

Keywords: Spherical Near-Field Measurements, Antenna Measurements, Measurement Error Budget, Uncertainty Analysis, Range Alignment

1.0 Introduction

The standard reference on spherical near-field scanning measurements is the volume entitled "Spherical Near-Field Measurements" edited by Prof. Jesper Hansen [1]. It contains an extensive report on the analysis of measurement uncertainties in spherical near-field scanning. The underlying work was carried out as a part of the original R&D program at the Technical University of Denmark. The study which appears as Hansen's Chapter 6 entitled "Error analysis of spherical near-field measurements," has been referred to often [3,4].

In addressing the needs of spherical near-field range design, we at MI Technologies have employed the TUD analysis as a starting point for new system layouts. I have expanded it in two ways: the approach to mechanical errors and the approach the system design.

A portion of the TUD uncertainty analysis is an analysis of the effects of mechanical inaccuracies. In this paper, I offer an alternative approach to the analysis of mechanical uncertainties. This alternative approach is based upon an earlier treatment of spherical coordinate positioning analysis for far-field ranges [2]. The result is an appropriate extension of the TUD uncertainty analysis that utilizes the ideas of the far-field range analysis and the TUD near-field analysis.

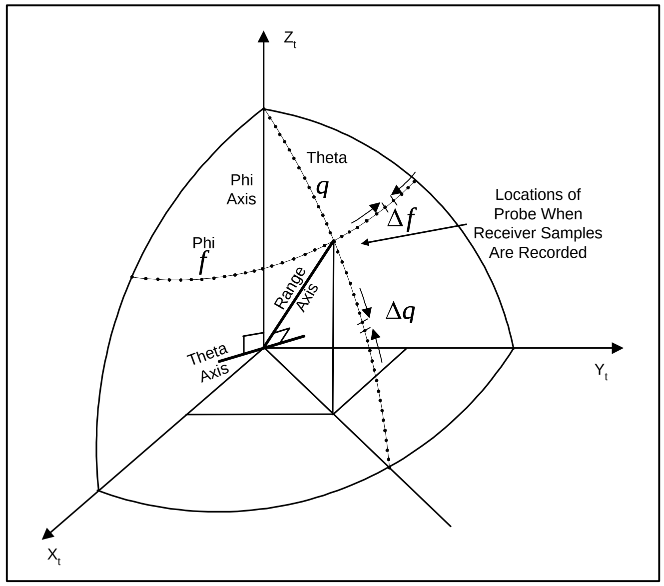

Figure 1. The Measurement Coordinate System and Grid Points Representing Positions of the Probe Origin when the Received Signal is Sampled.

2.0 The Concept of the Quality Factor

The basic purpose of spherical near-field scanning measurement is to sample the response of the probe when it is located at specific grid points on the measurement sphere, where the spacing of the grid points is dictated by the electrical size of the antenna under test:

$$\Delta\theta\ ,\ \Delta\phi \leq \lambda/D_{min} \text{ radians} \quad .$$

Here θ designates the polar angle and ϕ designates the azimuthal angle. Also, λ is the free space wavelength and D_{min} is the diameter of the minimum sphere -- the smallest sphere, centered on the crossing point of the two scanning axes, that encloses all sources of radiation. The measurement sphere is distinct from the minimum sphere. It is rigidly fixed to the antenna under test. The measurement sphere is the surface that the probe scans over during the measurements. For the radius to be accurately known and to possess a unique value, it must be held constant during the scanning process to within a small fraction of a wavelength. This requirement can be written as

$$\Delta R_{meas} \leq \lambda/F_Q \quad ,$$

where R_{meas} is the radius of the measurement sphere – i.e. the range length – and F_Q is a quality factor that ranges typically from 10 to 100. From planar near-field scanning we know that a scan plane needs to be flat to within approximately $\lambda/20$ to $\lambda/100$ or even better. Similarly for spherical scanning a sphere needs to be defined to within $\lambda/20$ to $\lambda/100$, depending upon the quality of the measurements to be made.

The accuracies $\delta\theta$ and $\delta\phi$ with which the record increments are defined may be related to the record increment values also by this quality factor:

$$\delta\theta,\delta\phi \le (1/F_Q)\ \Delta\theta,\Delta\phi = (1/F_Q)\lambda/D_{min}\ .$$

Often we desire to hold these uncertainties to very small values – especially when accurate boresight requirements apply to the range design.

A spherical near-field positioner is built up out of two primary stages of motion – one corresponding to phi and one to theta. I impose upon these two stages individually, requirements that will insure that a fixed radius will be held and that angular samples will be accurately recorded.

3.0 The MI Technologies Standard Error Budget

I begin the description of the standard error budget entries with the attributes of the individual active motion stages. To achieve excellent positioning accuracy out of each of the phi and theta motion stages I require that the following parameters be controlled:

Theta Uncertainties

10. Delta-Theta Deviation due to Phi Motion -
    Bearing Accuracy
11. Position Readout Uncertainty
12. Uncertainty -- Automatic Settability of Step Axis

Phi Uncertainties

14. Delta-Phi Deviation due to Theta Motion -
    Bearing Accuracy
15. Position Readout Uncertainty
16. Uncertainty-Readout Timing Error of Scan Axis ,

where the numbers refer to the tabulated list at the end of the text. Similarly, to control the radius of the scanning sphere, the following parameters must be held to close tolerances:

Radial Uncertainties

5. Error in Determination of Value for Radius
6. Delta-R Deviation due to Theta Motion -
   Bearing Radial Run-Out
7. Delta-R Deviation due to Theta Motion -
   Angular Wobble of Bearing
8. Delta-R Deviation due to Phi Motion -
   Bearing Radial Run-Out
9. Delta-R Deviation due to Theta Motion -
   Angular Wobble of Bearing

The most common configuration of a spherical near-field positioner is the roll-over azimuth configuration made up of two rotary axes stacked together [6]. Please see Fig. 2. The lower axis is always the theta axis and the upper axis is always the phi axis. Here I have assumed that the theta axis is the step axis and the phi axis is the scan axis. If they are interchanged then the uncertainties 12 and 16 will accordingly be interchanged.

In this roll/azimuth configuration, the range axis or line of sight is horizontal and fixed in space. Many other configurations are possible, including those where the line of sight moves in space and those where the range axis is fixed on a slant or even vertical. The descriptions of the uncertainties I give here are intended to be free of any specific reference to gravity – such as the terms vertical or horizontal.

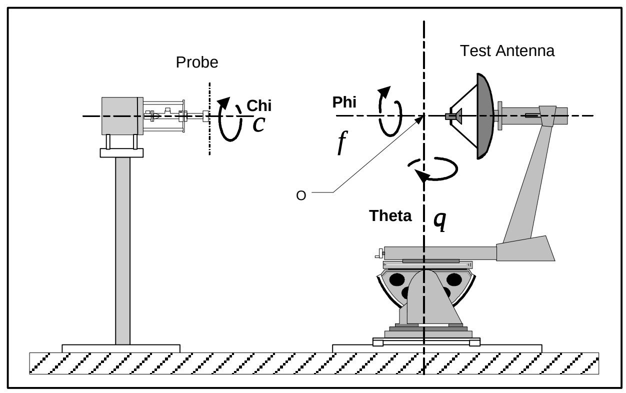

Figure 2. – Configuration of a Typical Spherical Near-Field Range where Roll and Azimuth are the Active Scanning Axes.

In a typical range the probe antenna is mounted on a roll or polarization positioner to permit it to be rotated about its cylindrical axis. The rotation allows it to respond successively to the theta and the phi components of the radiated electric field. This rotation angle is designated as chi (χ) in the mathematical model. Alternatively, a dual-ported probe antenna can be used to sense the two components simultaneously, making the polarization axis optional.

For a complete probe-pattern-corrected measurement there must be a fiducial coordinate system defined for the probe antenna. The origin of this coordinate system will lie at the center of the probe's aperture. It is fundamental that the probe's origin is centered on the range axis (or line of sight). This condition is insured by placing close tolerance limits on the following parameters:

Translational Position of Probe

13. Displacement of the Center of the Probe Aperture
    Parallel to the plane of Theta Motion
    (Horizontal Depointing).

17. Displacement of the Center of the Probe Aperture Perpendicular to the plane of Theta Motion (Vertical Depointing Error).

(The terms Horizontal Depointing and Vertical Depointing are Hansen's and I include them here to permit ready identification with Reference 1.)

The probe must in fact be aligned so that its cylinder axis is coincident with the range axis; this makes its cylinder axis intersect the origin of the spherical coordinate system. This gives rise to two additional constraints on the orientation of the probe:

Uncertainty in Angular Tilt Alignment of the Probe Axis

22. Uncertainty of the Probe Tilt Alignment in a Plane Parallel to the Plane of Theta Motion.
23. Uncertainty of the Probe Tilt Alignment in a Plane Perpendicular to the Plane of Theta Motion.

Because the received signal is relatively insensitive to the orientation of the probe axis, the probe tilt alignment is not exceedingly critical. However, accurately placing the center of the probe aperture at a designated grid point during scanning is critical for accurate pattern results – and most especially for accurate boresight results.

The constraints upon the polarization motion stage and the theta and phi motion stages that a careful uncertainty analysis addresses are:

Chi Uncertainties-Probe Rotational Alignment About Chi

18. Position Readout Error of the Chi Axis
19. Chi-Twist Due to Theta Motion
20. Chi-Twist Due to Phi-Axis Wobble
21. Alignment of Probe Rotation Around Probe Axis

Usually these four uncertainties are of secondary importance unless polarization properties are critical.

The build up of a two-axis positioner, entails mounting one axis over another and thereby incurring the effects of bending or compliance in the mechanical parts. Deflection errors must be considered also when mounting a test antenna of any substantial mass. I make three entries into our Table of error contributors to account for any mechanical deflections that cannot be compensated.

Axis Deflection Errors

24. Theta Axis Deflection due to Load or Temperature
25. Phi Axis Deflection due to Load or Temperature
26. Chi Axis Deflection due to Probe Loading or Temperature

The load referred to in 24 and 25 may be the load due to the test article or the load due to the upper stages of the test positioner. In some cases it will be necessary to expand this section of the uncertainty budget to account for each of the possible deflection sources. In an ideal roll-over-azimuth positioning system it is possible to compensate for every load by adjustment or counter-weighting, making the entries here negligibly small. At low frequencies the mass of a probe horn can be consequential and the corresponding deflection of the polarization axis support must be allowed for in the error budget. The effects of temperature can be significant unless the positioner is in a temperature-controlled environment.

In many spherical near-field ranges there are additional axes – axes that are not either a theta, a phi or a chi axis. For example in Figure 2 there is shown an elevation axis and a lower slide axis underneath the test positioner. There are always influences from the compliance or the setting of these additional axes and these additional axes can impose unwanted changes in the probe response. Here I make an entry for those additional errors due to axes that are not used in the scanning process.

Miscellaneous System Specific Errors

30. Effects of Additional Axes

4.0 Uncertainties in a Two-Axis Positioner

In Section 3 I discussed the basic requirements upon motion stages and what to consider to set up a probe in a spherical near-field range alignment. However, there is a more orderly approach to follow in aligning a spherical near-field range. First one takes the two rotary scanning stages and combines them together them proper relationship to each other. This proper relationship derives from the basic measurement coordinate system of Figure 1. The upper phi axis must intersect the lower theta axis for the probe to scan a spherical surface at a constant radius. And, the upper phi axis must be orthogonal (i.e. perpendicular) to the lower theta axis for the usual phi-theta paths to be traced out on the sphere by the origin of the probe's coordinate system. To the extent the axis stack-up does not meet these two criteria, I have mechanical uncertainties that appear in the table as

Two-Axis Sub-System Uncertainties

1. Non-Intersection Error Between Theta and Phi Axes
2. Non-Orthogonality: Theta Axis -to- Phi Axis .

These are the fundamental requirements on any two-axis spherical-coordinate scanner. Together with readout accuracy they assure a constant radius and proper theta-phi coordinates designating the position of the probe on the scan sphere.

Next, in aligning a range, the range axis must be defined. From Figures 1 and 2, one can see that the range axis should be defined as the line that connects the crossing point of the two scan axes with the center of the probe aperture. On a roll-over-azimuth range, that is perfectly aligned, the range axis will be horizontal and the phi- and chi- axes will be coincident with it. But, if the range is not perfectly aligned, the range axis must be defined more explicitly. One laboratory-based definition is as a line perpendicular to the lower theta axis and intersecting the center of the probe aperture. From Figure 1, it can be seen that the range axis must be perpendicular to the theta axis. To the extent that it is not, there is a range alignment error known as a collimation error [2]. This can be analyzed for the probe position (theta-phi) errors that it causes.

(Another useful definition of the range axis is that of the line defined by the phi axis for the settings Theta = 0 and Phi = 0. This refers it to the test antenna coordinate system rather than the laboratory.)

Often, one encounters the situation where the range is aligned by pointing the upper phi axis at the center of the probe aperture by adjusting the tilt of the theta axis using, say, with the elevation axis of the test positioner in Figure 1. Presuming that theta and phi remain orthogonal, one has then a collimation error brought about by a modest difference in the heights of the probe aperture and the axis crossing point above the level floor.

There is another type of range alignment error that can appear to arise when checking the pointing direction of the phi axis for the case theta = 0. The phi axis should pass through the center of the probe aperture for theta = 0. If it does not, the phi axis and the range axis are not coincident for theta = 0. This is usually handled by resetting the zero of theta. Alternatively one can redefine the range axis and re-adjust the probe antenna so that the condition is corrected.

The following two range alignment errors derive originally from the earlier analysis of uncertainties of far-field ranges but apply equally well to spherical NF ranges

Two-Axis Sub-System Uncertainties

3. Non-Orthogonality: Between Line-of-Sight and the Theta-Axis (Collimation Error)
4. Offset of Phi-Axis-Theta = Zero Position

5. Alignment of the Test Antenna to the Test Positioner

When setting up an antenna measurement on a spherical axis positioner, one must align the fiducial coordinate system of the test antenna with the coordinate system of the antenna positioner. Usually this is done with a set of accurate mechanical sensors such as a theodolite, a laser or a clinometer. If this is not done accurately (or more often not done at all) then the pattern measurement may not be readily reproduced. The uncertainties that define the associated errors are the Euler angles associated with a skewed mounting orientation:

Antenna Coordinate Axis Alignment Errors

27. Euler Angle Alpha
28. Euler Angle Beta
29. Euler Angle Gamma

In most antenna measurements the control of the three translational parameters of the test antenna relative to the test positioner are neglected, as those only influence the far-field phase pattern. These too should be added for a complete analysis in the case of far-field phase patterns, but are not included here.

This concludes our enumeration of the mechanical error contributors.

6. Uncertainty Analysis of a SNF Measurement System

The foregoing discussion covers the mechanical subsystem uncertainties. As Chapter 6 of the Hansen volume describes, the contribution of the reciever-related errors is also very important. I expand the list of receiver-related items offered by Hansen to be more explicit in the identification of contributors. Please see Table 1. Most important are the contributions from cable variations. The allocation of receiver-related errors derives directly from the receiver data sheet of the unit employed in the measurement facility of the Technical University of Denmark. Remarkably, nearly identical considerations apply in today’s era of technology.

Following Hansen as well, I include explicitly contributions due to the influence of probe correction uncertainties, and to spherical surface truncation. These influences can be found by perturbation of data and observation of the results.

I have added a set of contributors to gain measurement errors following the Newell analysis, as Hansen emphasizes the measurement of directivity rather than gain.

Lastly, I mention the influence of extraneous stray signals as an important contributor to uncertainties in the far-field pattern. To a very good approximation, we have found that the influence of the stray signals on the far-field pattern as in the near-field on a equivalent stray signal basis, aside from the effect of processing gain in the NFFF algorithm. The NFFF processing gain is typically 6 to 10 dB. Thus one can improve the suppression of stray signals in his near-field pattern by the use of the spherical near-field algorithm.

7. Summary

An expanded approach to spherical near-field uncertainty analysis has been described and tabulated in the tables found on the following two pages. It includes all of the entries found in earlier analyses – the Hansen reference, the Scientific-Atlanta reference and the NIST 18 term analysis [1,2,5].

				Table 1. MI Technologies Error Budget for Spherical Near-Field Measurements						
					Main Beam			First Null	First Side Lobe	Cross-Polar Lobe
					Directivity/ Gain	Cross-Polar Level	Beam Width	Position	Level	Level
					dBi	dB	Degrees	Degrees	dB	dB
				Error Category	Change in dB	Change in dB	Change in Degrees	Change in Degrees	Change in dB	Change in dB
A.	Mechanical Inaccuracies									
		Two-Axis Sub-System Uncertainties								
			1	Non-Intersection Error Between Theta and Phi Axes						
			2	Non-Orthogonality: Theta Axis -to- Phi Axis						
			3	Non-Orthogonality: Line-of-Sight to Theta-Axis (Collimation Error)						
			4	Offset of Phi--Axis-Theta=Zero Position						
		Radial Uncertainties								
			5	Error in Determination of Value for Radius						
			6	Delta-R Deviation due to Theta Motion - Bearing Run-Out Radially						
			7	Delta-R Deviation due to Theta Motion - Angular Wobble of Bearing						
			8	Delta-R Deviation due to Phi Motion - Bearing Run-Out Radially						
			9	Delta-R Deviation due to Theta Motion - Angular Wobble of Bearing						
		Theta Uncertainties								
			10	Delta-Theta Deviation due to Phi Motion - Bearing Accuracy						
			11	Position Readout Error						
			12	Position Automatic Settability Error						
			13	Loc. of Probe Cntr.-Par. to Theta Motion (Hzntl.Depoint.)						
		Phi Uncertainties								
			14	Delta-Phi Deviation due to Theta Motion - Bearing Accuracy						
			15	Position Readout Error						
			16	Readout Timing Error of Scanning Axis						
			17	Loc. of Probe Cntr.- Perp. to Theta Motion (Vert Depoint.)						
		Chi Uncertainties - Probe Rotational Alignment About Chi								
			18	Position Readout Error						
			19	Chi-Twist Due to Theta Motion						
			20	Chi-Twist Due to Phi-Axis Wobble						
			21	Alignment of Probe Rotation Around Probe Axis						
		Probe Alignment Uncertainties - Probe Tilt- Parallel & Perpendicular toTheta Plane								
			22	Probe Tilt Alignment Uncertainty Par. To Plane of Theta Motion						
			23	Probe Tilt Alignment Uncertainty Perp. To Plane of Theta Motion						
		Axis Deflection Errors								
			24	Elevation-Theta						
			25	Azimuth-Phi						
			26	Polarization -Chi						
		Antenna Coordinate Axis Alignment Errors								
			27	Euler Angle Alpha						
			28	Euler Angle Beta						
			29	Euler Angle Gamma						
		Miscellaneous System Specific Errors								
			30	Effects of Additional Axes						

		Table 1. MI Technologies Error Budget for Spherical Near-Field Measurements						
			Main Beam			First Null	First Side Lobe	Cross-Polar Lobe
			Directivity/ Gain	Cross-Polar Level	Beam Width	Position	Level	Level
			dBi	dB	Degrees	Degrees	dB	dB
		Error Category	Change in dB	Change in dB	Change in Degrees	Change in Degrees	Change in dB	Change in dB
B.	Receiver Inaccuracies							
	31	Amplitude						
	32	Phase						
	33	Thermal Noise						
	34	Cross-Talk						
	35	Linear Drift						
	36	Temperature Drift						
	37	Scan Velocity - Measurement Delay						
		- Measurement Response						
	38a	Cable Variation in Amplitude vs Motion						
	38b	Cable Variation in Phase vs Motion						
	39a	Cable Variation in Amplitude vs Temperature						
	39b	Cable Variation in Phase vs Temperature						
	40	Signal leakage						
C.	Errors Associated with Probe Correction							
	40	Measurement of Probe Reflection Coefficient						
	41	Measurement of Probe Gain On-Axis						
	42	Measurement of Probe Polarization On-Axis						
	43	Measurement of Probe Pattern -Hemisphere						
D.	Errors Associated with Gain Measurement							
	44	Insertion Loss Measurement						
	45	Antenna Reflection Coefficient Measurement						
E.	Truncation							
	46	Effect of Truncation in Theta or in Phi						
F.	Extraneous Signals							
	47	Probe-toTest Antenna Multiple Reflections						
	48	Signal Leakage						
	49	Chamber Reflection - Influence on FF Pattern						
G.	Other Identified Influences							
	50	To Be Supplied						

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