ALIGNMENT OF A LARGE SPHERICAL NEAR-FIELD SCANNER USING A TRACKING LASER INTERFEROMETER

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Abstract

In this paper, we describe the process used to align a large spherical near-field test system. The probe positioner consists of a cantilevered arc design with a probe path radius of five meters and a scan angle of 180°. The AUT positioner consists of an MI Technologies Model 51230 azimuth positioner with a high-precision encoder. The system is aligned using an SMX Tracker 4000 tracking laser interferometer.

Alignment into a spherical system is achieved by initially defining two cylindrical systems; a primary probe positioner based system and a secondary, AUT positioner based system. Sources of mechanical error in each of these systems are identified and techniques used to control these error sources are described.

Keywords: Spherical Near-Field, Tracking Laser Interferometer, Metrology

1.0 Introduction

Spherical near-field measurements are a standard for fully characterizing many classes of antennas to a high degree of accuracy. MI Technologies has developed a new spherical near-field measurement system that is based on the precise alignment between two single-axis positioners (Figure 1). Each of these positioners has a cylindrical coordinate system that is inherent to the positioner geometry. A spherical system is formed by aligning the two cylindrical systems so that their axes are orthogonal to one another. These axes then define the azimuth (ϕ) and elevation (θ) angles of the spherical system.

The azimuth positioner is an MI Technologies model 51230 azimuth turntable with a high-accuracy Inductosyn encoder. The article-under-test is mounted

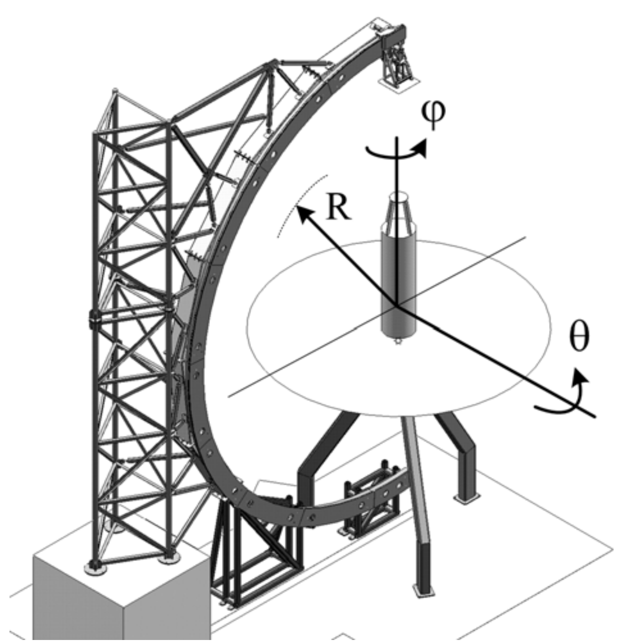

Figure 1: Isometric view of the spherical near-field measurement system.

to the turntable of this positioner which is capable of continuous motion through a full 360° of rotation.

The elevation axis of the spherical system is an MI Technologies Model 6850-224-180 circular scanner that is based on a cantilevered-arc design. This scanner is designed to move an RF probe around the circumference of a circle with a five meter radius. The probe moves through an elevation angle of 180°, from a position in which the probe points down vertically to a position in which the probe points straight up.

2.0 Geometric Errors

There are several different geometric errors that affect the overall accuracy of a spherical near-field measurement system. An extensive analysis of these errors and their effects on spherical near-field measurements is beyond the scope of this paper. Such an analysis may be found in References 1 and 2. In this paper, we will focus on five geometric errors that have a critical effect on testing of electrically large antennas. The first of these is an error in the radial distance between the electrical center of the AUT and the aperture of the test probe (ΔR error). The second and third are errors in the measured values of the ϕ and θ angles. The fourth and fifth are intersection and orthogonality errors between the nominally intersecting and orthogonal ϕ and θ axes.

Table 1 lists the acceptable limits for each of the five errors. For each error, we list a corrected and an uncorrected value. In order to increase the useable frequency range of the spherical near-field system we have incorporated a secondary, error-correction mechanism into the system. The values in the second and third columns of Table 1 reflect the allowable errors before and after the secondary corrections are applied. The error correction mechanism is discussed in more detail in Section 4.0.

Geometric Error	Uncorrected Limit (+/-)	Corrected Limit (+/-)
Radial Distance (ΔR)	0.44 mm.	0.24 mm.
Azimuth Angle (Δϕ)	0.013°	0.008°
Elevation Angle (Δθ)	0.010°	0.005°
Axis Intersection	0.38 mm.	0.38 mm.
Axis Orthogonality	0.01°	0.01°

Table 1: Limits on Geometric Errors for the Spherical Near-field System

Each geometric error has multiple sources in the spherical near-field system. In the following sections we will describe the positioners in more detail and discuss attributes of the positioners that contribute to the geometric errors. We will then describe our method for constructing and aligning the system so that the geometric errors are bounded below acceptable levels. At the time that this paper was written no measured results of the system shown in Figure 1 were available, however measured results are presented for a very similar circular scanner. This scanner is identical to the one shown in the figures except that it has a scan angle that runs from the vertical (θ = 0) position to an elevation angle of θ = 130° and it does not have the error correction mechanism.

3.0 The Azimuth Axis

The azimuth axis of the cylindrical system is formed by the axis of rotation of an MI Technologies Model 51230 azimuth positioner. This positioner is supported by a steel tripod and mounted on an adjustable mount. The mounting system of the azimuth positioner is illustrated in Figure 2. Four pairs of opposing jacking screws provide translational adjustment in a plane parallel to the top of the azimuth stand. Three leveling feet facilitate the tilt adjustment for the azimuth axis.

The AUT is mounted to the positioner turntable. The nominal position of the AUT relative to the positioner is such that the primary axis of the AUT is collinear with the axis of the azimuth positioner. The turntable has a set of registration pins that facilitates alignment of the axis of the AUT relative to the axis of the positioner. Tilt of the AUT axis is accomplished using an adjusting mechanism that is built into the customer's mounting fixture.

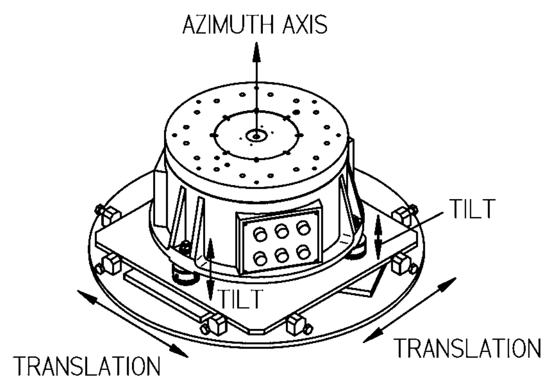

Figure 2: The azimuth axis adjusting mechanism

3.1 Azimuth Axis Error Sources

The most significant sources of geometric error for the azimuth positioner are those errors associated with bearing runout and encoder accuracy. The ΔR error is affected by both the axial and radial runout of the bearing. The AUT is moved away from the ϕ axis by the amount of the radial runout as it rotates. The total radial runout of the bearing is 0.051 mm. or +/- 0.0254 mm. Therefore the maximum ΔR error caused by the radial runout is 0.0254 mm. at θ = 90°.

The axial runout causes the azimuth axis to "wobble" away from the ϕ axis. This angular error is manifested as an error in R at the AUT aperture which is a considerable distance away from the bearing ball path. Given the total axial runout of 0.051 mm. for the bearing, the bearing ball path diameter and the maximum AUT aperture height, the ΔR error at the AUT aperture is 0.102 mm.

Angular position of the azimuth axis is measured and controlled using an Inductosyn encoder. The error in the measured values of the angle ϕ is within 0.005 degrees as achieved by the encoder and the drive system.

4.0 The Circular Scanner

The elevation axis of the spherical system is formed by a circular scanner that utilizes a cantilevered-arc design. As shown in Figure 1, this scanner consists of a set of nine circular track segments that are supported by a set of structural steel tube. Each track segment is mounted to its corresponding support tube using a mounting system that allows adjustment in six degrees of freedom of motion. The track segments are designed so that the outside curved surface and the front face form the primary and secondary datum surfaces for controlling the motion of the probe carriage. The probe carriage engages the track using precision cam rollers to clamp against these datum surfaces.

Motion of the probe carriage around the circumference of the circle is measured using a linear encoder that is mounted flush with the outside curved surface (the primary datum) of the guide track. This encoder measures the arc length of carriage travel to a resolution of 10 µm. This linear resolution translates into an angular resolution of the elevation axis of 1.0 x 10^{-4} degrees.

4.1 Circular Scanner Error Sources

The primary mechanical error sources for the circular scanner are:

1) Deviation in the local radius of curvature of the outer surface of the guide track – This component error can lead to errors in the radius of the sphere and errors in the elevation angle. The magnitude of this error is bounded to be less than 0.13 mm. by the track machining specification.
2) Deviation in the flatness of the front face of the guide track – This component error can cause the probe aperture to tilt out of the plane of the nominal probe path. This leads to an error in the measurement of the angle ϕ and to an error in the radius of the sphere. This error is bounded to be less than or equal to 0.20 mm. by the guide track machining specification.
3) Encoder accuracy errors – This error leads to errors in the elevation angle. The maximum magnitude of this error is 29 µm. which corresponds to an elevation angle error of 2.9 x 10^{-4} degrees.
4) Track segment alignment errors – The design of the cantilevered-arc scanner is such that virtually all geometric errors are a result of machining errors in the track segment datum surfaces or in alignment between the track segments. Alignment of the track segments affects all five of the spherical system geometric errors. The degree to which the track segments can be brought into alignment with one another is the primary factor determining the overall accuracy of the scanner.

5.0 Error Correction Mechanism

In order to increase the maximum frequency at which the spherical near-field system can be used, we have incorporated a secondary, error-correction mechanism into the circular scanner. This system is designed to apply corrections in three directions: 1) A rotation about the elevation axis ($\Delta\theta$), 2) A translation along the radial direction (ΔR), 3) A translation along the direction normal to the plane of the scan circle (ΔP). The $\Delta\theta$ correction is accomplished using the existing elevation axis drive train. ΔR and ΔP corrections are accomplished using a pair of orthogonal linear actuators that are mounted on the probe carriage (Figure 3).

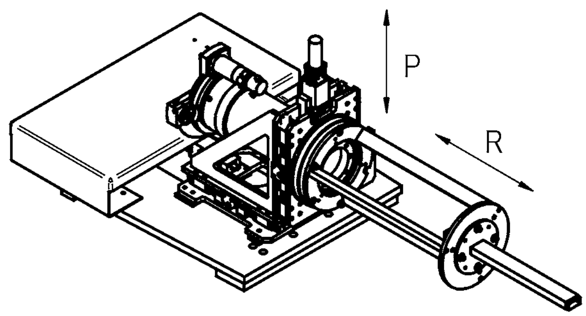

Figure 3: The error correction stage

The error terms that are used to generate corrections are based on an error map. This map is constructed using direct measurements of the path of the RF probe aperture as it moves around the scan circle. These measurements are taken by mounting the corner mirror target of the tracking laser interferometer at the probe aperture location, then moving the probe carriage through its full scan range. Points are recorded at 0.05° elevation angle increments.

The error map is stored as point data in the MI Technologies Model 4193 Position Controller that is used to control the circular scanner axes. Correction terms for elevation positions that are between data points are calculated using liner interpolation between the adjacent data points. As the probe carriage moves around the circular arc, real-time adjustments are made to each of the three corrected axes.

6.0 Construction and Alignment of the Spherical Scanner System

Alignment of the spherical scanner system is an iterative process that begins during the construction phase of the system. Throughout the construction and alignment process we utilize an SMX Tracker 4000 tracking laser interferometer (SMX) to align components to one another and to gravity. This instrument can track and measure the location of a corner-mirror target over distances of up to 30 meters. The relative positions of points located diametrically opposite one another on the 10 meter diameter scan sphere can be measured to an accuracy of 0.06 mm. (Reference 3). Software provided with the SMX allows the user to collect point data over a path, perform a best-fit registration of a perfect-form geometric entity to the point data, and construct spherical, cylindrical and Cartesian coordinate systems based on these best-fit geometric entities.

The general procedure for the construction and alignment of the spherical scanner system is outlined below. A more detailed discussion of the procedure follows this higher-level description:

1) A Cartesian coordinate system is constructed using the gravity vector as the primary axis. A secondary (clocking) axis and an origin are constructed using surfaces of the test chamber (e.g. the chamber walls).
2) Using the Cartesian system from step 1, the position of the circular scanner in the room is located. The circular scanner is constructed and “rough-aligned” in this coordinate system.
3) The arc of the outside curve of the circular scanner track is scanned with the SMX and a best-fit circle to this measurement is constructed. This circle is used to define a cylindrical coordinate system whose origin is the center of the best-fit circle and whose primary axis is the normal vector to the plane of the best-fit circle. The gravity vector is used as the secondary axis of this system.
4) Using this cylindrical system, the circular scanner is iteratively “finish-aligned.
5) The final position and orientation of the circular-scanner based system is used to define the spherical near-field coordinate system. The origin of this system is the center of the best-fit scan circle. The plane of this circle is used to define the $\phi = 0$ axis and the projection of the gravity vector into the best-fit scan circle is used to define the $\theta = 0$ axis.
6) The azimuth axis is erected on its supporting tripod. The corner mirror is positioned at the edge of the azimuth turntable and point data is collected as the table is turned through a full rotation. The point data is used to generate a best-fit circle. The center and normal vector of this circle define the position and orientation of the azimuth axis.
7) The azimuth mount adjusting mechanisms are used to make the azimuth axis collinear with the spherical system ϕ axis.

As described, the spherical coordinate system in which the spherical near-field measurement is taken is based on the cylindrical system that is defined by the circular scanner. This approach allows us to maximize the accuracy of the circular scanner by iteratively aligning it to itself. This approach results in higher precision than that which would be achieved by attempting to align the scanner to some external reference.

6.1 Alignment of the Circular Scanner

In this section we provide a more detailed description of the alignment of the circular scanner using the SMX tracking laser interferometer. As discussed in the last section, we begin the construction process by defining a Cartesian coordinate system that is based on the gravity vector and chamber attributes such as the walls. Using this system, the triangular tower is positioned and anchored to the floor. The steel support struts and one of the track support tubes are then assembled to the tower. At this point, a translation is applied to the Cartesian coordinate system so that the system origin is located at the end of one of the track support standoffs. The standoff coordinates are checked against the CAD model of the circular scanner. The mounting struts that support the tubes have an adjusting mechanism that allows the position and orientation of the tubes to be adjusted. As each successive support tube is assembled onto the scanner its position is checked against the CAD model using the SMX. This approach ensures that the final assembly of tubes forms a set of chords that define a circle with roughly the correct radius and orientation.

Once all of the track support tubes have been assembled and positioned, the first guide track segment is assembled onto the support tube. The position and orientation of the track segment is checked against the CAD model by using the SMX to measure the location of tooling points that are machined into the front face of the track. Once the first track segment is correctly positioned and oriented, the remaining track segments are successively added to the scanner. As before, the coordinates of the tooling points are checked against the CAD model in order to ensure that the track segments are in roughly the correct orientation.

At this point in the alignment process, the track segments are aligned in roughly the correct position. The next step in the alignment process is to take SMX measurements around the outer perimeter of the track in order to define an initial best-fit circle. Figure 4 is a plot of the radial deviations from the best-fit circle after this initial measurement for the circular scanner that is composed of six track segments. Note that the misalignment of each of the individual segments can easily be distinguished.

Based on measurements of the track perimeter, the track segments are iteratively adjusted and re-measured until they form a smooth, flat arc. At this point the drive gear is assembled onto the scanner and the probe carriage is positioned on the track.

For alignment and measurement purposes, a "probe simulator" is used. This probe simulator is designed to position the corner mirror at the same position as the aperture of the actual RF probe and to have the same mass and deflection characteristics as the actual RF probe.

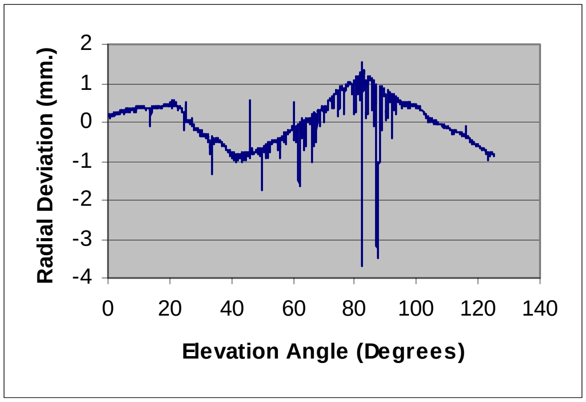

Figure 4: Radial deviation of rough-aligned track segments from the best-fit scan circle

With the corner mirror positioned on the probe simulator, a measurement of the scan circle is taken by driving the probe carriage around the scan circle and collecting a data point every 0.1" of arc length. *Note that by using the probe simulator and drive carriage to position the corner mirror this measurement tracks the same path that would be followed by the aperture of the RF probe in an actual measurement.* This means that adjustments that are made to the track positions are based on errors in the actual path of the probe aperture. By measuring the aperture path directly, we account for all sources of geometric errors, including deflections due to the moving load of the probe carriage and rotations of the carriage due to combined track geometry errors.

The aperture path is repeatedly measured and adjusted until errors are within the specified tolerance limits. Figures 5 and 6 show plots of the radial deviation and planar deviation for the 130° circular scanner after it has been aligned. Final radial accuracy is +/- 0.33 mm. and final planar accuracy is +/-0.76 mm. This planar error results in a ϕ error of 0.009°.

Once the track segments have been brought into alignment the linear encoder scale is attached to the outside curved track surface. In order to obtain accurate measurements of the elevation angle θ, it is necessary to derive a scaling factor that gives an accurate value for the number of encoder counts per degree of travel.

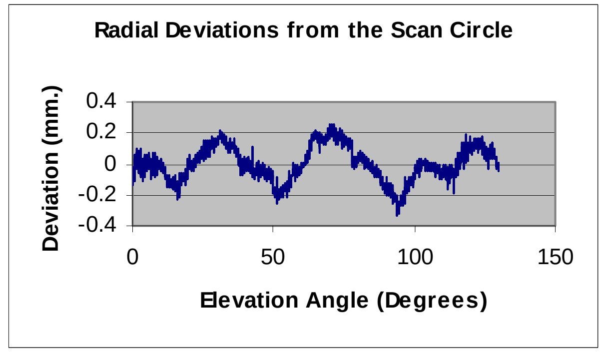

Figure 5: Radial deviations from the scan circle for the aligned 130° circular scanner

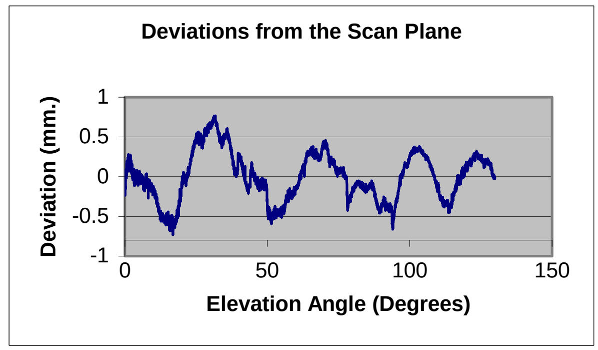

Figure 6: Normal deviations from the scan plane for the aligned 130° circular scanner

Figure 7 gives a plot of elevation angle accuracy for the 130° circular scanner. This plot was generated by moving the probe carriage in 1° steps with the corner mirror mounted at the probe aperture position. At each step the elevation angle as measured by the SMX (considered to be the correct angle) was compared with the elevation angle reported by the position controller. Over the entire travel range the elevation angle accuracy was +0.006°/-0.003°.

6.2 Alignment of the Azimuth Axis in the Spherical System

Alignment of the azimuth axis takes place after the circular scanner alignment is completed. Accuracy of the azimuth angle is inherent in the design of the positioner and is set when the positioner is built at the factory. Thus, alignment of the azimuth axis is strictly a matter of finding the location and orientation of the axis and bringing it into alignment with the spherical coordinate system.

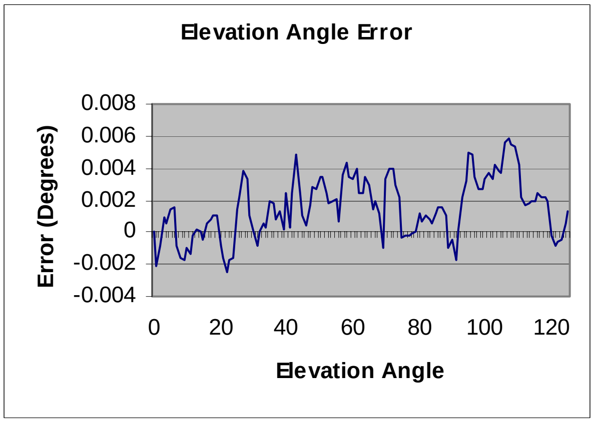

Figure 7: Elevation angle error for the aligned 130° circular scanner

Measurement of the axis location and orientation is performed by mounting the corner mirror on the azimuth turntable, near its edge. As the turntable rotates, data points of the corner mirror positions are taken using the SMX. The data are processed to obtain a best-fit circle. The azimuth axis is the vector normal to the plane of the circle and through the center of the circle.

Using the three leveling feet on the azimuth mount, tilt adjustments are made in order to make the measured azimuth axis parallel to the spherical system ϕ axis. A new azimuth axis location is then measured. This process is repeated until the azimuth axis is parallel to the ϕ axis to within the specified tolerance.

Next, translational adjustments are made to the azimuth positioner in order to make the azimuth axis collinear to the system ϕ axis. The azimuth position is iteratively adjusted, re-measured and re-adjusted until the axes are collinear to within the specified tolerance.

The non-intersection error between θ and ϕ axes is determined by measuring accuracy of the laser and the translational adjustment resolution of the positioner mounting system. For this measurement, the accuracy of the tracking laser interferometer is 0.04 mm. The translational adjustment resolution is 0.25 mm. or better. Therefore the non-intersection error is not greater than 0.29 mm.

The non-orthogonality error between θ and ϕ axes is determined by measuring accuracy of the laser and the tilt adjustment resolution of the positioner mounting system. The laser accuracy establishes the uncertainty in locating of the θ axis and the azimuth axis. The uncertainty in orthogonality of θ and ϕ axes is quantified as 0.0055 degrees. The linear resolution of each leveling foot is better than 0.002”. The tilt adjustment resolution for the azimuth axis is therefore 0.0057 degrees. The total non-orthogonality error is 0.008 degrees if RSS of the two error terms is used.

7.0 Conclusions

We have described a method for the construction and alignment of a spherical near-field scanner system that is based on two single-axis positioners. The elevation positioner is a new design based on a cantilevered circular arc. The proper alignment of this positioner is critically dependent on the effective use of an SMX tracking laser interferometer. Use of this instrument allows us to directly measure and adjust the path of the RF probe aperture. Using this approach we are able to construct an elevation axis with a 5 meter radius that has an angular accuracy of better than 0.006°.

We have also described the use of the SMX tracking laser interferometer to bring an azimuth positioner into alignment with the elevation positioner to form a highly-accurate spherical system. We have shown how effective use of the tracking laser interferometer allows us to perform system level alignment without resorting to time consuming optical or limited RF means.

References

[1] Hess, Doren W., “An Expanded Approach to Spherical Near-Field Uncertainty Analysis,” Antenna Measurement Techniques Association 24th Annual Meeting & Symposium (AMTA-02), Cleveland, OH, pp 495-500.

[2] Hansen, J.E., *Spherical Near-Field Antenna Measurements*. Peter Peregrinus Ltd., 1988.

[3] SMX Corporation, “SMX Tracker 4000/4500 Operator’s Guide”, 2001.