A PRECISION OPTICAL RANGE ALIGNMENT TECHNIQUE

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ABSTRACT

Spherical near-field testing and other specialized antenna measurements require precise range and positioner alignment. This paper presents a method based on optical techniques to conveniently measure and monitor both range alignment and the positioner axis orthogonality and intersection. The hardware requirements consist of a theodolite and a unique target mirror assembly viewable from either side.

INTRODUCTION

The function of an antenna test positioner is to move an antenna or antenna system in a prescribed manner to enable a "probe" to measure the actual radiation emitted in a particular direction of interest. Measurements are usually made in spherical coordinates, with the antenna under test at the origin. The positioner must be chosen to provide adequate load capacity, accuracy, and structural integrity. Positioners are available to carry loads from 50 to 50,000 lbs and it is possible to accurately measure angles of 0.05° with synchros or 0.005° using precision encoders. Structural integrity involves the dynamic effects of a load in motion and also includes the geometric perfection of the positioner. Dynamic effects may be minimized by selecting a positioner with the proper capacity. Axis intersection and orthogonality are two aspects of a positioning system geometry which will be discussed in this paper, and a method for accurately and reliably adjusting these parameters will be presented.
ORTHOGONALITY AND INTERSECTION IN ANTENNA TESTING

Positioning hardware has developed based on the fact that "accurate enough" orthogonality could in most cases be built into the positioner. The popular positioners have met this expectation well. The azimuth-over-elevation (AZ/EL) positioner, probably the most common configuration, provides heavy structure between the axis and places them in close proximity to one another. (See Figure 1.) It is easily within normal machining tolerances to provide orthogonality within 1 milliradian. Since orthogonality error has a second order effect on the measurement accuracy, this error has also been acceptable.

![Diagram of positioner](image)

**FIGURE 1. AZIMUTH-OVER-ELEVATION POSITIONER**

Axis intersection error has often been justifiably ignored. This is because when measuring an antenna pattern using conventional techniques, the effect of non-intersection is a parallax imposed on the data. This parallax is immaterial for an amplitude measurement, and unless phase measurements are being made can be ignored. Some positioner configurations, elevation-over-
azimuth (EL/AZ) for example, may actually have an inherent axis offset because of other measurement or convenience aspects of that configuration. (See Figure 2.)

FIGURE 2. ELEVATION-OVER-AZIMUTH POSITIONER

In recent years, two factors have independently acted to return attention to orthogonality and intersection. First, antenna technology has increased the performance of antenna systems dramatically. As the frequency of antennas has increased, wave length has decreased, and positioner related dimensions must be reduced accordingly. High performance antenna systems also frequently require phase and amplitude testing to properly optimize the design. A second driving force for better control of the positioner geometry is the development of practical near-field testing. Phase and amplitude data are required for pattern transformation to far field in order for this powerful method to yield accurate results. Numerical aspects of spherical near-field testing encourage antenna mounting configurations which are not as structurally rigid as the AZ/EL positioner (for example a roll-over-azimuth positioner). The emergence
of these needs has encouraged the development of a method to easily and accurately set and verify the axis intersection and orthogonality of an antenna test positioner under load.

PREREQUISITES FOR IMPLEMENTATION OF THE METHOD

With certain limitations to be discussed below, the technique presented is general. There are some geometrical prerequisites:

1. The two test axes must each have at least $180^\circ$ of motion.

2. Some provision must be made on the positioner to adjust the orthogonality and intersection of the upper axis with respect to the lower axis.

3. The upper axis must have a thru center hole.

4. With no load on the turntable, an unimpeded view in the direction of the range axis thru the center hole of the upper axis must be possible at the two points $180^\circ$ apart in the lower axis travel.

5. The lower axis must be sufficiently stable under the load shifting normally encountered during the test sequence.

6. If alignment of the source positioner is required, the unloaded positioner must provide for a clear line of sight from behind the positioner thru the positioner coordinate system origin, to the source.

THEORY OF THE METHOD

In this section, a general outline of the method and an implementation technique will be presented. A detailed procedure for a typical positioner alignment is provided in the appendix. Although the theory is general, a
specific configuration, roll-over-azimuth (ROLL/AZ) (see Figure 3), has been assumed for this discussion. Adaptation of this technique to other orientations such as a slant range will be presented in the next section.

FIGURE 3. ROLL-OVER-AZIMUTH POSITIONER

The test equipment required consists of
- Precision clinometer (less than 3 arc sec accuracy is normally required)
- A special two-way spindle target mirror assembly
- Autocollimating theodolite and stand with horizontal and vertical linear adjustment provisions
- A target or target mirror assembly as appropriate for the source positioner and type of testing to be performed
Each of the procedures used in this method is based on an "indirect" measurement of a specific parameter. The essence of this principle is that a perfectly oriented configuration will yield an expected result. Utilizing a knowledge of the characteristics of perfect alignment, the degree of non-alignment and necessary corrective action may be determined.

The procedures required to align a ROLL/AZ positioner and range are as follows. NOTE: A detailed procedure is contained in the appendix.

1. Adjust the lower axis vertical and determine that the stability under motion is within acceptable limits.

2. Adjust the two-way spindle target mirror coincident with the roll axis.

3. Adjust the theodolite coincident with the roll axis.

4. Rotate the lower (azimuth) axis exactly 180°.

5. Measure the intersection and orthogonality error and readjust these parameters as necessary.

6. Reset the theodolite on the roll axis and use this optical axis as the alignment reference for the source positioner.

To adjust the lower axis vertical, a clinometer is placed on the turntable such that the bubble vial axis roughly intersects the axis of motion. Several readings are taken at various angles about the range of motion. A perfectly vertical axis would yield an identical clinometer reading for any arbitrary angular position. The degree and direction of inclination can be determined by an analysis of the results of the measurements. Another result of the inclination measurement is an indication of the non-uniform compliance of the lower axis. This variation in bending may be the result of non-symmetric base positioner or a non-uniform mounting pad. The change of the clinometer readings of a vertical axis describes the stability of that
axis. The exact test program will determine the system accuracy specifications based on the positioner geometry, and the intersection and orthogonality requirements.

The key innovation of this technique is the use of a two-way spindle target mirror assembly (Figure 4) to optically define an axis of rotation. A spindle target mirror provides linear adjustments for translating the center of the mirror target coincident with an axis of rotation and angular adjustments for tilting the mirror face perpendicular to the axis.

To set the target mirror coincident to the axis, the principle of noting the deviation from perfect alignment is utilized. The theodolite is placed such that it is autocollimated with the mirror. The axis is rotated 180° and the required movement of the theodolite to reacquire azimuth and elevation autocollimation is measured. The theodolite is moved to the center of these two readings and the mirror is readjusted to autocollimation. One or more repetitions of this procedure may be required to minimize error. At this point, the mirror face is perpendicular to the axis of rotation. The theodolite is then focused on the mirror target and similar steps are repeated to place the crosshair of the target on the axis of rotation. It is not necessary that the theodolite be referenced to the axis to perform the mirror alignment. The theodolite is then aligned coincident with the axis of motion using these same principles by adjusting the theodolite and positioner until the theodolite crosshairs simultaneously are aligned with the target and are autocollimated.

Axis intersecton and orthogonality errors are determined at the same time by rotating the lower axis until azimuth autocollimation is re-established. (This is exactly 180°.) (See Figures 5 and 6.) To eliminate parallax effects, the mirror is designed with a target etched in a single reflective coating on one mirror face only. The glass faces are parallel, so that when viewing the target thru the glass, the angle of incidence is 90°. Refraction of the image is negligible. Figure 5 shows graphically an intersection error condition after the 180° rotation and Figure 6 shows an orthogonality error. The error interpretation may be made by considering a perfect alignment. With perfect geometry, the target would be on the same line of sight and also would
a) PHOTOGRAPH OF INSTALLED MIRROR

b) DESCRIPTION OF ADJUSTMENTS OF TWO WAY MIRROR ASSEMBLY

FIGURE 4. TWO WAY SPINDLE TARGET MIRROR ASSEMBLY
FIGURE 6. GRAPHIC DESCRIPTION OF ORTHOGONALITY ERROR
be autocollimated and centered on the theodolite crosshairs. When focused on the target, the horizontal displacement of the theodolite required to recenter the target mirror on the theodolite crosshair represents twice the intersection error. The elevation displacement required to re-establish elevation autocollimation represents twice the orthgonality error. After moving the theodolite to the midpoint of these error ranges, the upper axis of the positioner must be adjusted to coincide with the theodolite axis.

After the above adjustments are complete, the positioner axes intersect and are orthogonal, and the theodolite is a reference to which the source positioner may be aligned since it is perpendicular to the lower axis and coincident with the upper axis. Depending on the electromagnetic characteristics of the probe and the nature of testing to be performed (far-field, near-field, probe-corrected near-field), the probe positioner may be translated and/or rotated as appropriate, using the theodolite as the coordinate system reference.

FEATURES OF THE METHOD

An important feature of this method is its versatility with respect to any range of test loads. Since during initial alignment, the requirement of a line of sight through the turntable would prevent the loading of most test antennas, the method must provide for realignment after installation of the load. With the theodolite oriented as described above, ready realignment of the test positioner is possible. To re-establish and check alignment, the following procedure may be followed after a test load is installed:

1. Recheck the lower axis inclination to assure that the additional load has not created excessive instability of the lower axis.

2. Although the structure will probably sag under load (see Figure 7), the theodolite remains an accurate reference. Therefore, orthgonality may be reset simply by readjusting the roll axis for elevation autocollimation of the target mirror.
FIGURE 7. REESTABLISHING ORTHOGONALITY UNDER LOAD
3. Due to an eccentric torsional load on the roll axis, some wobble will occur due to load shifting. The extent of this wobble can be measured by watching the target motion under load. It should be noted that this motion is a structural deformation and cannot be adjusted, but merely monitored.

Using the above procedure, the orthogonality and intersection may be set and verified for any load configuration.

In principle, this method may be used on a range in any orientation, but some structural deflections may not be identified using this technique. For example, a slant range has loading conditions which can require additional instrumentation to identify all possible error conditions. Two of these errors involve the bending of the offset arm assembly under the side loading imposed by the slant configuration. The first is measurable using the two-way mirror assembly and the linear vertical adjustment of the theodolite. Figure 8 depicts this configuration and displays the measurement of the error. The effect of this distortion is an orthogonality error:

\[
\psi = \tan^{-1} \left( \frac{d}{2X_p} \right)
\]

For small errors, the vertical displacement of the theodolite is very small, and the error may be more easily determined by comparing the elevation angle of the theodolite with the inclination of the lower axis.

\[
\psi = \alpha_{ELEV} - \alpha_{INCLINATION}
\]
\[
\psi = \tan \left( \frac{d_y}{2x_p} \right)
\]

**Figure 8. Inherent Orthogonality Error of a Slant Range**

- **Orthogonality Error**
- **True Normal to Lower Axis**
- **Range Slant Angle**
- **These Two Axes Are Parallel and Would Indicate Proper Orthogonality**
- **Vertical Displacement**
There is a second error of a slant range which cannot be detected using only these techniques. This error is an intersection error when the roll axis is perpendicular to the range axis, and is shown in Figure 9. A method of determining the major component of this intersection error involves referencing the upper axis to the lower axis to detect intersection error. The details of how this might be done will not be discussed here. The significant point to note is that neither of the two errors discussed with regard to a slant range nor any other non-symmetrical effects due to gravity cannot be "adjusted out" of a positioning system, but must be minimized by constructing the positioner such that it is sufficiently stiff to withstand those loads and remain "accurate enough."

SUMMARY

The method presented in this paper is a precision means of optically setting the intersection and orthogonality of two appropriately configured positioner axes. Major characteristics of this technique are:

1. Axis intersection may be set within 0.010".

2. Axis orthogonality may be set within 5 arc sec.

3. Orthogonality may be reset easily for an arbitrary load.

4. Upper axis stability under motion may be directly measured.

5. A definition of the range axis is inherent in the technique.

6. The source positioner may be oriented linearly and angularly to the range axis using this method.

7. This technique works best for a positioner with a vertical lower axis.
FIGURE 9. INHERENT INTERSECTION ERROR OF A SLANT RANGE
Appendix

1. Measurement of Axis Inclination

   a. Determination of the Axis Position

      The axis position is determined by measuring the change in inclination of a reference surface as a function of rotation. The direction of inclination may be related to (a) a zero point established by geometry of the positioner, (b) the range coordinate system, or (c) magnetic compass direction.

   b. Placement of the Clinometer

      Place a clinometer on a smooth surface of the turntable and clamp in place to prevent accidental movement. The clinometer bubble vial shall be initially aligned with the 0-180 degree azimuth line of the coordinate system with the right-hand side (facing the engraved dial) of the clinometer pointing toward zero azimuth.

   c. Measurement Procedure

      Level the bubble of the clinometer and read the micrometer scale. Rotate the azimuth turntable 30 degrees clockwise and repeat the leveling and reading. Continue clockwise rotation and record all data for 360° or the range of motion of the lower axis.

      The setting and reading of azimuth angle values is usually not critical. Values recorded are to be within ±3° as indicated by the position indicator system. The clinometer angle values are to be read and recorded to the nearest 5-second increment. At each leveling, the bubble of the clinometer is to be returned, within 1/2 mark, (2-mm graduation of vial) to the initial level position.
If the indication of an axis in a particular vertical plane is desired, only two clinometer readings are required. Utilize the orientation described in paragraph b, but rotate clockwise 180 degrees for the second reading.

d. Interpretation

The tabulated values may be plotted on cross-section paper with azimuth angles as the abscissa and clinometer angles as the ordinate. For a stable (fixed) axis, the resulting curve is a sine function with one cycle equal to 360 degrees azimuth. The direction of axis inclination is the azimuth angle having the lowest value of clinometer angle. The magnitude of inclination is equal to one-half the difference between the highest and lowest values of inclometer angle.

The stability of the axis may be approximated by observing the deviation from a "true" sine function defined by a best fit curve drawn thru the data points.

2. Adjustment of Two-Way Spindle Target Mirror Coincident with Axis of Motion

The adjustment of the spindle target mirror involves two adjustments: orthogonality and intersection.

Adjusting the Spindle Target Mirror Perpendicular to an Axis

a. Place the mirror on the mounting plate approximately on the axis.
b. Rotate the axis until opposite tilt adjustment screws define horizontal and vertical lines.
c. Adjust the theodolite for autocollimation and record the azimuth and elevation readings on the theodolite.
d. Rotate the axis 180°, readjust the theodolite for autocollimation, and record the theodolite readings.
e. Determine the midpoint between each pair of azimuth and elevation readings and mechanically set the theodolite to that value.
f. Adjust the mirror using the tilt adjustment until the theodolite is autocollimated.

g. Repeat steps c) through f) until the variation is within 4-5 seconds of arc. (This will typically involve 2 or 3 iterations.)

Adjusting the Spindle Target Mirror Target to Intersect an Axis

a. Rotate the axis until opposite translation adjusting screws define horizontal and vertical lines.
b. Using the theodolite as a telescope, align the target in the theodolite crosshairs and record the azimuth and elevation readings of the theodolite.
c. Rotate the axis approximately 180°, readjust the theodolite to align with the target and record the theodolite readings.
d. Determine the midpoint between each pair of azimuth and elevation readings and mechanically set the theodolite to that value.
e. Adjust the mirror using the translation adjustment until the target aligns in the crosshairs.
f. Repeat steps b) through e) until the variation is within 4-5 seconds of arc. (This will typically involve 2 or 3 iterations.)

3. Placement of a Theodolite on an Axis

a. Adjust the theodolite to autocollimate the mirror (previously adjusted perpendicular and coincident to the axis).
b. If the required offset is within the range of the linear translation stages of the theodolite, center the theodolite crosshair telescopically on the mirror target. Repeat steps a) and b) as necessary until autocollimation and alignment are both present without readjusting the theodolite.
c. If the linear offset range is not sufficient for step b) above, an iterative technique must be used. Using the azimuth and elevation scales of the theodolite, measure the angular difference between autocollimation and telescopical alignment and position the theodolite to the midpoint between these two readings. Move the positioner azimuth
axis and the roll tilt adjustment to reestablish autocollimation. Repeat steps a), b), and c) if necessary until the conditions of step b) are satisfied.

4. Measurement of Intersection and Orthogonality Error

a. Adjust the spindle target mirror coincident with the roll axis. (See Appendix Procedure 2.)

b. Place the theodolite on the roll axis. (See Appendix Procedure 3.) Note the readings of the theodolite and its translation stages.

c. Rotate the positioner in azimuth by exactly 180.00°. The positioner is in the correct position when azimuth autocollimation is reacquired without any readjustment to the theodolite or its translators.

d. Reacquire elevation in addition to azimuth autocollimation as well as mirror crosshair targeting using the theodolite and its associated hardware. Note the theodolite AZ, EL and translation readings.

e. Set the theodolite to the midpoints between readings obtained in step "b" and "d" above for AZ, EL, and horizontal translation.

f. Readjust the positioner until autocollimation and crosshair targeting are acquired. Repeat steps "b" through "f" until one half of the deviation between the two readings is within acceptable tolerances.