Gimbals For Antenna & Radome Measurement: Demanding Applications Drive Innovative Architecture, Remarkably Higher Accuracy

J Mark Hudgens
MI Technologies
Suwanee, GA, USA
mhudgens@mitechnologies.com

George M. Cawthon
MI Technologies
Suwanee, GA USA
gcawthon@mitechnologies.com

***Abstract*— For the purposes of antenna or radome measurement, a gimbal may be thought of as a compact, two or three axis antenna positioner with mutually orthogonal, intersecting axes. The unrelenting demand for higher accuracy in positioners of this type is driving innovation in mechanical architecture and design. Refined position feedback techniques, reflecting enhanced understanding of position errors, and delivering unprecedented native encoder accuracy, have been developed and tested. New mechanical architecture has been created that allows for fully-featured two-axis gimbals to exist in the restricted confines behind an aircraft radome. The principal result of these developments is increasingly accurate and capable systems, particularly in the field of radome measurements. These new applications, techniques, architectures, and their results are explored in the following pages.**

I. INTRODUCTION

A. *Background*

Fourth generation fighter aircraft typically employ a mechanically scanned fire control radar antenna. This antenna resides in the nose of the aircraft behind an aerodynamic radome, through which the antenna's beam must pass. A gimbal positions the antenna to collect azimuth, elevation, and range data in support of the calculation of a firing solution. The gimbal/antenna assembly is mounted to an aircraft bulkhead within the radome volume.

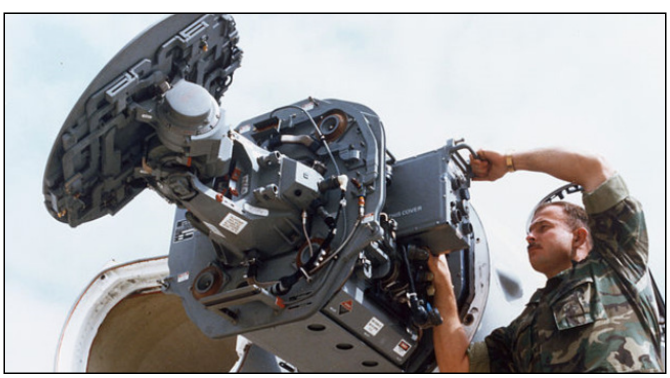

Figure 1. Mechanically Scanned Fire Control Radar (Raytheon Photo)

Figure 1 depicts a fourth generation fighter aircraft with a mechanically scanned radar antenna. The gimbal is visible behind the monopulse antenna. The radome is hinged on the left side of the picture, and is shown pivoted largely out of view.

Radome measurement concerns itself with primarily RF beam deflection, transmission efficiency and antenna pattern distortion of the radar beam as it passes through the radome. These tests are performed to qualify new or repaired radomes [1]. In support of this testing, an actual fire control radar antenna is mounted to a purpose-built test gimbal, both residing inside the subject radome. The geometry of the fighter aircraft radar and radome is maintained in the radome measurement system. In other words, the test gimbal, antenna, and radome are intended to closely mimic the actual flight hardware in their essential functions, and their mounting configuration and geometry reflect this. A radome measurement gimbal (or *test gimbal*) is therefore usually specific to a particular antenna and radome [2].

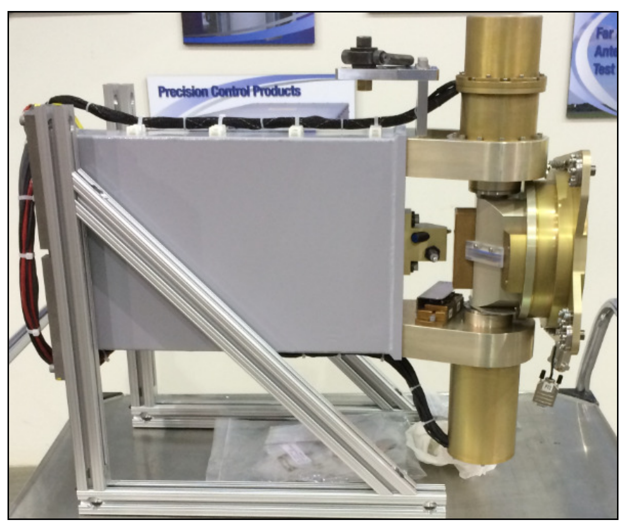

Figure 2. Roll / Azimuth Gimbal on Stand

Radome testing requires two sets of measurements, first without and then with the radome over the radar test antenna. Measurement accuracy requirements of RF boresight error (beam deflection error) due to radome effects, is in the range of ± 0.1 mrad. Generally, the radome test system may be classified as a closed loop tracking system or an electronically calibrated system. For the tracking system, the gimbal's angle encoders are used to indicate beam deflection. In the electronically calibrated system, the gimbal's encoders are used to calibrate the radar antenna's tracking error voltages (which are used to indicate beam deflection). In either case, a high precision gimbal with high accuracy position readouts is required.

B. Definition of Terms

Gimbal: A compact, precise, two (or three) axis positioning system specifically intended to orient radar antennas. Gimbals are electric servo devices that employ position and rate feedback.

Encoder: An electromechanical device that converts an angular position to an electrical signal.

Accuracy: In a rotating system, the kinematic measure of fidelity of the intended motion or position. In static machine elements, the measure of fidelity of surface and axis geometric relationships. Often used interchangeably with *error*. Expressed in linear or angular units.

Running Accuracy: The kinematic deviations of surface or axis position as a result of rotation about an axis.

Encoder Accuracy: The difference between an encoder's self-reported angular position and the angular position of a co-rotational independent measurement instrument. May be measured dynamically or statically.

Encoder Repeatability: In a rotational system, the variation in multiple angular position measurements of the same point under the same conditions.

Kinematics: A branch of mechanics concerned with motion, but not inertia. Kinematics may be thought of as the study of the geometry of motion. Kinematic error, for example, is mechanical position deviation that exists due to geometry conditions only.

Runout: Kinematic error of a surface or an axis caused by surface geometry error or by rotation about an axis with imperfect bearings. Runout may be expressed in angular or linear units. Angular runout is usually measured optically. Surface runout is usually measured mechanically, and expressed in linear units.

Axis: A line about which an object rotates. Axes are virtual, in that there are no mechanical features of machine elements that exactly correspond to them. Rotational axes are generally defined by ball bearings or ball bearing systems.

Axial: Referring to an axis of rotation, the direction along an axis.

Radial: The direction normal to an axis.

Direct Drive: A motor-driven mechanical drivetrain that eschews gears, belts, couplings, etc. in favor of mounting the motor directly to the load.

C. Unit Convention

Where two types of units are customarily used, both will be presented, as with expressions of angular accuracy: ± 12.6 arcsec (± 0.0035 deg). Where a single type of unit is used almost exclusively, then dual dimensions will be eschewed in favor of the type in common usage. For example, the dial indicator discussed below is graduated in .0001 inch increments, and there seems little purpose in presenting dual units every time the reading of the indicator is discussed.

II. GIMBAL ARCHITECTURE

A. Primary Gimbal Requirements

1) Capacity: The gimbal must have sufficient strength and stiffness to support and position the payload (usually an antenna) without unacceptable structural deflection or other error.

2) Configuration: The gimbal must have the correct number of axes to accomplish the measurement system goals. The axes must be configured (azimuth/elevation, roll/azimuth, etc.) according to the measurement requirements.

3) Size & Geometry: The gimbal must fit in the space defined by the flight hardware (antenna, flight gimbal, and radome) geometry. It must also be small enough to be shadowed by its antenna.

4) Range of Motion: The gimbal must provide a range of motion for all of its axes that is sufficient for the test regimen.

5) Accuracy: The gimbal must move the antenna to commanded positions with sufficient accuracy to satisfy the test regimen. Some test regimens have an accuracy requirement for dynamic tracking of the antenna.

B. Configuration

The traditional description of positioning systems for antenna measurements takes the form of, for example, *roll/azimuth or azimuth/elevation*, pronounced "roll over azimuth" or "azimuth over elevation". The word "over" designates that one axis is carried by another. For example, an azimuth/elevation/roll gimbal has three axes; the azimuth axis is carried by the elevation axis, which is carried by the roll axis. Test gimbals often have the same configuration as their corresponding flight gimbals. Sometimes the test gimbal is configured differently in support of specific testing regimens.

C. Motors

MI Technologies' gimbals exclusively use brushless direct-drive motors on all axes. A direct drive motor is a frameless type consisting of a rotor, stator, and a circuit board containing Hall effect switches and a thermistor. The rotor is mounted to the gimbal axis shaft. The stator is mounted to a cylindrical housing. The circuit board is usually integral with the stator as provided by the manufacturer. Advantages offered by direct drive motors over conventional drive systems include zero backlash and very low compliance. Gimbal dynamics and accuracy are greatly enhanced as a result.

D. Encoders

An encoder is an electromechanical device that provides digital (or sometimes analog) information based on shaft position or displacement. Gimbals rely on encoders for position and rate feedback in the context of a precision servo system. Direct drive encoders consist of a graduated ring or disk and a sensor (or sensors) for reading the graduations. Encoders may be incremental or absolute. Incremental types merely generate square-wave pulses as they are rotated. These pulses are counted by the control system to determine real-time position and rate. The pulse train generated by a moving incremental encoder is directional, allowing the control system to add or subtract as appropriate. Incremental encoders do not have the ability to report their position upon startup. Absolute encoders differ from incremental types in that their position is reported immediately upon power up. Both encoder types are capable of providing very high resolution and accuracy. Optical, inductive, or magnetic sensing technologies are available. All current MI Technologies gimbal encoders are optical in nature.

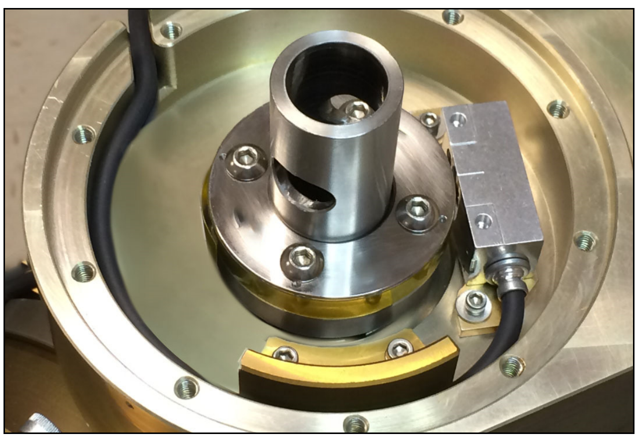

Figure 3. Direct Drive Encoder Installation

Position encoders are available in two basic configurations: (1) Packaged, including integral bearings, housing, and shaft, and (2) Direct drive, consisting of a rotating ring and a sensor. Direct drive types offer all the advantages mentioned previously concerning direct drive motors, and are thus used exclusively on all MI Technologies gimbals. A packaged encoder is much simpler to mount into a machine, but there are inevitable and unacceptable kinematic coupling errors in doing so. Since so often it is “all about accuracy”, every effort is made to eliminate sources of error where possible. Encoder rings are typically mounted coaxially with the motors that drive them, on the same torsionally stiff shaft. Figure 3 depicts a high precision direct drive encoder installation. The shaft in the figure is about 1” diameter. Further discussion of encoders follows.

E. Bearing Types and Arrangements

Ball bearings are used on all axes of motion. Specified and mounted correctly, they offer extremely good running accuracy and low rolling resistance, as well as a smooth transition from the static to the rolling condition. Angular contact types are most often used, with some axes benefitting from the use of 4-point contact types. On through shafts, duplex pairs of match-ground back-to-back angular contact bearings are in common use. Alternatively, if required by geometry constraints, a pair of thin-section bearings is mounted to a common shaft, separated by a few inches, and preloaded with a spring. All bearings are preloaded to eliminate clearance.

F. RF & Wiring Path

It is difficult to pass wiring and RF signals through a gimbal. Attempts have been made, mostly unsuccessful, to route gimbal wiring and antenna RF cables directly to their destinations without benefit of engineered cable management systems. Far more successful is the current use of slip rings and RF rotary joints in conjunction with hollow shafting. The hollow shaft in figure 3 serves as both a precision shaft and a wiring conduit.

III. Gimbal Accuracy

A. Considerations for Accuracy

Gimbals for Radome and antenna measurements are precision test instruments. As such, their accuracy is of prime importance, and generally exceeds that of their corresponding flight gimbal by at least an order of magnitude. Pursuit of accuracy is a top consideration in every step of gimbal design and manufacture. Accuracy has several components:

B. Kinematic Accuracy

Rotating machinery exhibits geometric errors which are often due to bearing imperfections, or more commonly, poorly mounted or implemented bearings. This is the dominant type of kinematic error in gimbals, since conventional drive components are routinely eschewed. Kinematic accuracy (or error….recall that the terms are often interchanged) is particularly important to a gimbal’s primary function: pointing an antenna. This type of error manifests itself in two important ways: (1) as a component of encoder error, and (2) as position error that is not witnessed by the encoders.

C. Encoder Accuracy

Encoder accuracy is complex; it has many components. The gimbal designer has no control over the error contributions that are intrinsic to the encoder components. These include, but are not limited to, (1) the imperfections of the graduations on the encoder disk, and (2) the interpolation error, both of which are fortunately small. However, the gimbal designer and builder enjoy significant control over other types of error, which fortunately tend to be the dominant ones. Discussion of these types of errors follows.

1) Encoder Ring Eccentricity: Assuming high quality bearings and a competent implementation, a major component of encoder error is the failure to mount the graduated encoder ring axis concentrically with the bearing system axis of rotation. An eccentric encoder ring will exhibit a "high spot" that varies sinusoidally with every rotation of the gimbal axis, resulting in a difference between the actual rotation angle and the indicated rotation angle. See figure 4. This first order encoder error is given by [3]:

$$\Delta\varphi = \pm 412(E/D) \qquad (1)$$

$\Delta\varphi$ = Measuring error (arcsec) = φ-φ'
E = Eccentricity between ring and bearing axis (µm)
D = Ring (or graduation) diameter (mm)

Eccentricity of the encoder ring relative to the bearing axis can easily be the dominant error within a positioning system. For example, for a 52 mm diameter encoder ring, the encoder error caused by only 25 µm eccentricity is ± 412 (25 µm/52 mm) = ± 198 arcsec (± 0.055 deg). This is an enormous encoder error, at least an order of magnitude above that allowed in most cases. Thus, encoders are extremely sensitive to eccentric mounting.

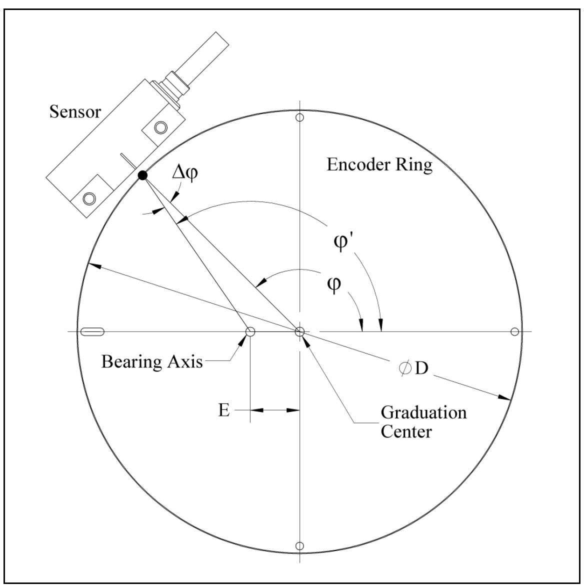

Figure 4. Kinematics of Encoder Eccentricity

2) Bearing Clearance: Clearance is defined as space between adjacent machine parts. In the context of the bearing system of a rotating encoder ring, it is disastrous. This is because the clearance is perceived by the encoder system as a first order error that is very similar to encoder ring eccentricity.

Fortunately, bearing clearance can be completely avoided. The outer bearing race generally is installed in a turned aluminum housing. For typical gimbal bearing sizes, up to 70 mm diameter, a transition fit with a tolerance zone size of 10 µm (.0004 inch) will generally suffice to achieve the desired zero-clearance fit at least material condition (LMC). The shaft fit is trickier. Zero clearance is still required, but it must be possible to assemble and disassemble the shaft into the bore of the bearing. Ground stainless shafting with tolerance zones as small as 5 µm (.0002 inch) are sometimes necessary. Hand lapping of the shaft may still be required to achieve the correct fit. Clearance within the angular contact bearing is eliminated by application of axial preload.

3) Ring Distortion: The first order errors of eccentricity and bearing clearance are established. Higher order harmonics are associated with encoder rings that are some shape other than round, which of course they all are. Overall shape distortion or localized high spots contribute to harmonic errors. The avoidance of significant higher order errors due to ring distortion involves competence on the parts of the encoder manufacturer and the user. The graduation radius of the encoder ring must be manufactured to be as constant as possible. That is, it must be *round.* Again, using the 52 mm ring as in previous examples, if its installed circularity (which is a minor component of runout) is maintained to better than about 1.3 µm (.00005 inch), experience has shown that the higher order harmonics become only minor contributors of encoder error.

4) ABEC Numbers & Kinematic Error: Precision ball bearings are available in various tolerance classes determined by the Annular Bearing Engineering Council (ABEC). A numbered designation system (ABEC 1,3,5,7,9) defines the maximum allowable inner and outer race runout for given diameters of bearings. For instance, a 30 mm bore ABEC 5 ball bearing must have no more than 5.1 µm (.0002 inch) radial runout of the outer race. Additional runout tolerances, bearing size and surface taper tolerances are similarly controlled.

It is a mistake to assume that a higher ABEC number will necessarily result in a better encoder installation. The installed difference in an ABEC 5 bearing and an ABEC 9 bearing for example, is trivial when compared to those first order errors discussed previously. Experience shows that ABEC 3 angular contact bearings, properly mounted, will allow an encoder system to achieve ± 18 arcsec (± 0.005 deg) accuracy. A high ABEC number bearing may provide some margin, making it easier to achieve desired accuracy, but their use is not always indicated.

There is one type of kinematic bearing error that will very likely improve with use of a high ABEC number bearing. That is *asynchronous runout.* As the name implies, it is not repeatable; not harmonic. Its magnitude is very small. Experience indicates that it can barely be detected in an ABEC 7 bearing when measuring runout on a mounted encoder disk with a .0001 inch reading dial indicator. Asynchronous runout is the result of the interplay between the microscopic features of the bearing balls and the races. It appears as noise on the encoder accuracy curve, and therefore cannot be nulled with traditional error correction techniques.

D. Direct Drive Encoder Accuracy Case Study

Consider the direct-drive encoder in figure 5. The ring is 100 mm diameter. It is mounted to a ground stainless steel shaft that is supported by a pair of ABEC 7 angular contact bearings. The bearing bore diameters are 4.00 and 7.00 inch. They are axially separated by 3.00 inches, and preloaded with a wave washer to about 350 pounds. The bearings are mounted back-to-back. The entire axis, and therefore the encoder, is driven by a brushless direct-drive motor. Maximum speed is 6 deg/sec.

The encoder in the figure is undergoing setup. The optical graduations are faintly visible on the ring's periphery. The task is to make the encoder ring axis concentric with the bearing system axis. Desired encoder accuracy for this application is ± 18 arcsec (± .005 deg), therefore the maximum permissible eccentricity is: 18 (100) / 412 = 4.37 um (0.00017 inch). Eccentricity cannot be measured directly because the rotational axis is a virtual entity. We therefore measure ring runout with the indicator, and infer the location of the bearing axis relative to the ring axis. Assuming a perfectly round encoder ring (a reasonable approximation, given the ultra-precision ring in the figure) mounted .00017 inch eccentric, its runout as measured with the dial indicator shown is predicted to be .00034 inch.

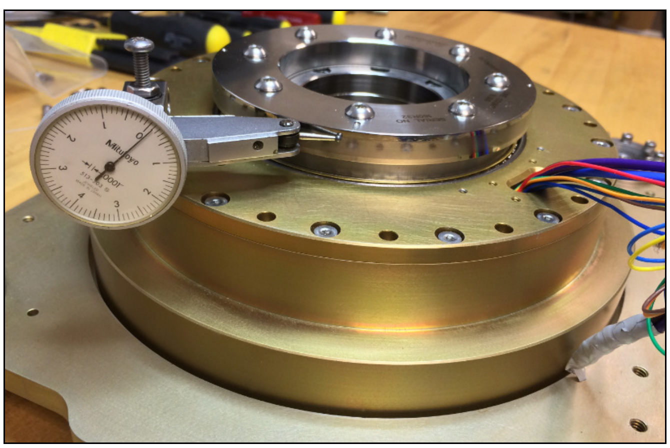

Figure 5. 100 mm Encoder Ring Calibration

So the setup goal is now quantified: make the ring axis and the bearing system axis sufficiently concentric so that the ring runout is less than .00034 inch. This "dialing in" of the ring is conceptually simple, but upon consideration of the tiny measurements and adjustments involved, may seem devilishly difficult to achieve.

The process of dialing in the encoder ring is iterative. The ring in figure 5 is mounted to a hub with 8 button head screws. Dialing in of the ring is performed with the screws loose so that the ring is free to radially translate within the limits of the screw clearance holes. A dial indicator with .0001 inch graduations is set up as shown. The axis is rotated by hand one full revolution, with the full indicator movement (FIM) noted. The axis is rotated again until the indicator has found its minimum reading, corresponding to the "trough" of the ring. Next, the ring is radially translated in the direction of the indicator such that ½ of the FIM reading is nulled. In other words, the ring is moved .0003 inch if the FIM is .0006 inch. The nulling process is iterated until the FIM can be made no smaller. This might take a few iterations, or all day, depending on the adeptness of the poor soul attempting it. Experience shows that a light tap with a hard object yields much more predictable results when adjusting the ring than a harder tap with a soft object. When the ring is adjusted such that the FIM of the indicator is minimized, its screws are tightened. Success is predicted if the runout of the ring is less than the calculated threshold, .00034 inch in this case. The actual measured runout is .00030 inch. The implied eccentricity is .00015 inch (assuming the simplest interpretation of the runout). Predicted encoder accuracy is therefore ± 412 (3.81 μm / 100 mm) = ± 15.7 arcsec (± 0.0044 deg). Figure 6 below depicts the result of this encoder subjected to a standard accuracy test.

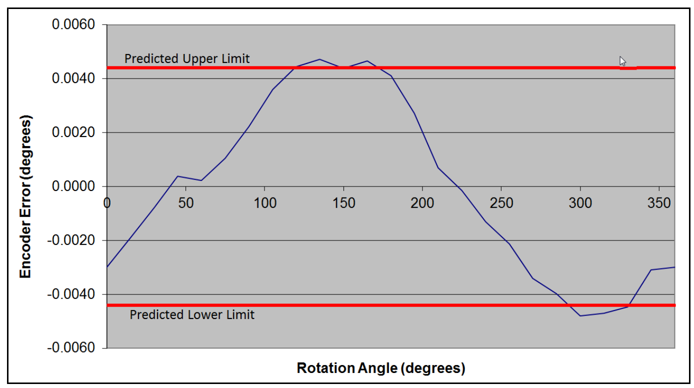

Figure 6. Direct Drive Encoder Accuracy Test Result

The blue curve depicts a series of points corresponding to $\Delta\varphi$ in figure 4. The red lines show the predicted limits of the curve. Predicted and actual encoder accuracies are in close agreement. The measured accuracy is ± 17.3 arcsec (± 0.0048 deg) The encoder error is dominated by eccentricity of the encoder ring relative to the bearing axis, as evidenced by the telltale sinusoidal shape of the error curve. While this first order error is dominant, higher order errors are implied. They are hard to identify though, being superimposed with asynchronous runout and human measurement error.

E. Other Considerations for Accuracy

The encoder system described above achieves impressive accuracy. Pushing the described techniques to their limits has achieved encoder accuracy as high as ± 12.6 arcsec (± 0.0035 deg), a truly impressive feat. Experience at MI Technologies indicates that encoder accuracy on this level is only achievable with direct drive systems employing the best encoder rings and bearings available and the highest levels of manufacturing precision. Historically, if higher accuracy is required, controls-based error correction is applied [4].

In encoder systems that are not direct drive, that is, systems employing flexible couplings (bellows, helicals, and the like); the native accuracy is difficult or impossible to push beyond ± 14.4 arcsec (± 0.0040 deg). This is due to the limiting effect of the flexible coupling, with its kinematic rotational error and its hysteresis. Geared encoder systems (dual-speed synchros, for example) are in another class entirely, typically providing order-of-magnitude poorer accuracy than discussed herein. These types of encoders are eschewed in gimbal design due to their lower accuracy.

F. Accuracy Results in a Real-World Application

A next-generation MI Technologies gimbal, designed and manufactured under the new paradigm described in the sections above, achieves unprecedented accuracy. Figure 7 below depicts the encoder accuracy test results for one axis of this direct drive gimbal. The native accuracy is an impressive ± 4.0 arcsec (± 0.0011 deg), a level that challenges the optical test instruments used to measure the errors.

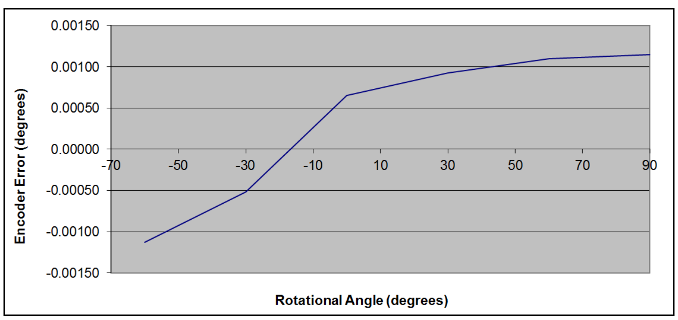

Figure 7. Dual-Sensor Encoder Accuracy Test Result

The range of travel of this axis is 150 degrees. We are denied a view of the telltale shape of a curve generated from a full 360 degree range of motion, and denied the insight often provided from such curves.

The curve is nevertheless useful. Not only does it depict the encoder error of ± 4.0 arcsec (± 0.0011 deg), it also exhibits a shape that is characterized as having a slope. A scale factor of 0.999985 applied at the control system to the encoder signal nulls the slope of the curve, resulting in an adjusted encoder error of about ± 1.5 arcsec (± 0.0004 deg). This is an astonishing level of encoder accuracy. See figure 8.

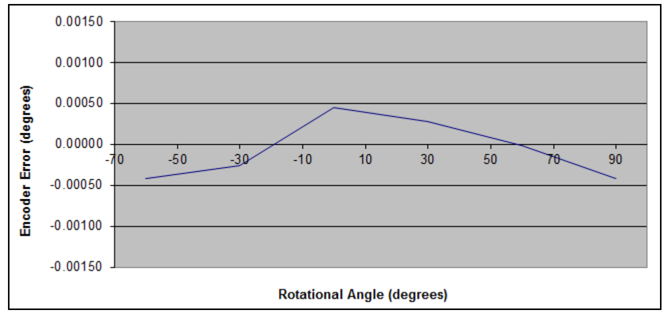

Figure 8. Encoder Error with Scale Factor Applied

Error curves that exhibit slope will not always appear, though they often do for ranges of motion of about 180 degrees and less. If they do appear, scale factors are routinely used to null the slope.

IV. SUMMARY

Measurement of beam deflection error due to radome effects requires a precision two-axis gimbal capable of high positioning accuracy and repeatability. This paper presents an increased understanding of the myriad of possible error contributors, and the innovative mechanical architecture and refined encoder techniques required to overcome them. Measured data has been presented showing impressive achieved native accuracy ± 4.0 arcsec (± 0.0011 deg) and an adjusted encoder accuracy of ± 1.5 arcsec (± 0.0004 deg).

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