EXTREME ACCURACY TRACKING GIMBAL
FOR RADOME MEASUREMENTS

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Abstract

Modern radome measurements often involve scanning the radome in front of its antenna while the antenna is actively tracking an RF signal. Beam deflections caused by the radome are automatically tracked by the antenna and its associated positioning system, which is typically a two-axis (pitch & yaw) gimbal. The motion required to accurately track the beam can be very demanding of the gimbal. High structural stiffness, zero drivetrain backlash, and extremely accurate angle measurement are all necessary qualities for radome beam deflection measurement. This paper describes a new, advanced, two-axis gimbal that embodies those qualities.

The new gimbal incorporates direct-drive motors to achieve zero backlash. The motors are mounted directly to the rotating gimbal elements, thereby eliminating the usual causes of drivetrain compliance. Rated torque of the motors is not high, and the antenna is therefore fully counterweighted.

Each of two optical encoders is mounted on the same rotating gimbal element as its associated motor. The encoders are directly mounted; no flexible coupling is used. The antenna is mounted to those same rotating elements. Antenna positioning error due to windup of the structure and drivetrain is virtually eliminated.

Eccentricity of the encoder disk, which is the primary source of direct-drive encoder errors, is adjusted by virtue of a remarkable *in situ* process.

Keywords: Gimbal, Positioner, Radome Measurements

1. Radome Measurement System Gimbal Requirements

The primary measured parameters for radomes are transmission efficiency, pattern distortion (or image lobes), and beam deflection. Angular beam deflection measurement accuracy requirements are typically 0.1 milliradians rms. This requirement dictates (1) that the gimbal accurately track the RF beam as it is deflected by the moving radome, and (2) that the encoder provide extremely accurate feedback over a wide travel range. These requirements dictate a stiff gimbal structure with wide servo bandwidths for both axes.

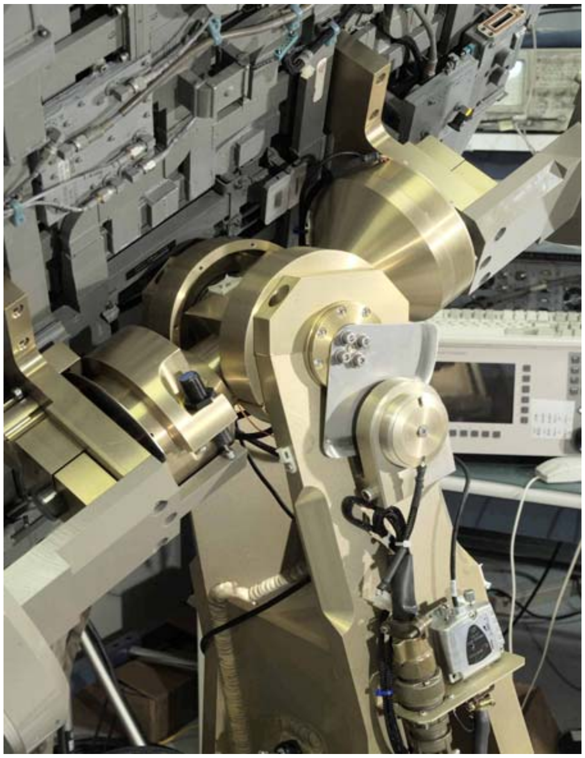

Figure 1. Gimbal With Antenna

Additionally, in the course of beam deflection measurements, the antenna is essentially stabilized in space as the radome is scanned about the antenna. It is necessary to decouple the antenna as much as possible from any high frequency vibrations generated by the radome positioner.

2. Gimbal Specifications

The performance specifications for the yaw axis of the extreme-accuracy gimbal are given in Table 1. Specifications for the pitch axis are similar, but are not presented due to space limitations.

Table 1. Yaw Axis Specifications

Characteristic	Specification
Drive Train Backlash	0.000 degrees
Axis Wobble	< .001 degrees
Axis Non-Orthogonality	< .05 degrees
Axis Intersection	< .005 inch
Fundamental Frequency	32 Hz
Maximum Velocity	5 degrees/sec
Minimum Velocity	.003 degrees/sec with no cogging
Cont. Delivered Torque	1.7 ft lb
Breakaway Friction Torque	< .04 ft lb
Running Friction Torque	< .02 ft lb
Antenna Imbalance	< .02 ft lb
Peak Delivered Torque	2.3 ft lb
Maximum Torque Ripple	< 5% average to peak
Torque Ripple Frequency	79 cycles/revolution
Position Feedback Type	Optical Incremental Encoder A quad B
Position Feedback Resolution	.0001 degrees/count
Position Feedback Accuracy	+/- .005 degrees (+/- 18 arc seconds)
Position Feedback Repeatability	+/- .001 degrees (+/- 3.6 arc seconds)
Operational Travel Limits	+/- 67 degrees
Typical Payload Weight	10 to 25 pounds
Approximate Weight (Including Antenna & Counterweights)	100 pounds

3. Highly Integrated Mechanical Design

Space for machinery between the antenna and gimbal axes is restricted, as is the space on the sides of the gimbal base that is swept by the antenna. To further complicate matters, both axes require very large ranges of travel – up to ± 67° in yaw and up to + 67° -30° in pitch.

Conventional positioning systems make use of drive components such as gears, flexible couplings, belts, and chains. The space restrictions referred to above, along with the demanding tracking requirements of the gimbal (zero backlash & very high stiffness), precluded the use of most types of conventional drive devices, and dictated a novel, highly integrated design.

A single housing, machined from a solid bar, encloses both motors and encoders, as well as all of the bearings. This monolithic housing allows gimbal geometry to be defined by the machining operations on a single part rather than being defined by the tolerance stackup of multiple parts. Axis orthogonality and intersection errors are thus a function of predictable machining tolerances. Gimbal stiffness and weight are also improved relative to an assembly of many parts. See Figures 2 and 5.

4. Bearings

The bearings selected for the gimbal are angular contact type, ABEC 9 quality. They are installed in a back-to-back configuration. The yaw axis makes use of two bearings separated by about 12 inches. The pitch axis makes use of 2 pairs of duplex bearings. All the bearings are lightly preloaded to eliminate clearance and minimize friction. Features of this bearing configuration and type are:

- Low friction allows partial decoupling of the antenna from radome positioner vibrations. Tracking errors due to gimbal base motion are kept to a minimum.

- High running accuracy minimizes axis wobble.

- Extremely small non-repeatable runout allows the encoders to perform optimally.

- Light preload allows gimbal to achieve high performance levels at any orientation.

5. Shaft & Housing

In some competing gimbal designs, the payload antenna must carry torque from one side of the gimbal to the other. This deficiency is completely eliminated by the new gimbal. Due to the solid shaft on the yaw axis, and the solid housing on the pitch axis, torque is applied symmetrically to all the antenna attachment points. It is therefore impossible to distort the antenna (and degrade its performance) by applying motor torque asymmetrically.

Another advantage of the solid shaft / solid housing design is the high torsional stiffness on both axes. The gimbal is so torsionally stiff that it contributes to raising the fundamental vibration frequency of the antenna. The solid shaft / solid housing design also provides virtually error-free coupling between the motors and their respective encoders. Torsional windup, for all practical purposes, is eliminated. Finally, the counterweight attachments to the yaw axis benefit from the stiffness and security of the solid shaft / solid housing design.

6. Motors

Motors for both axes are brushed, direct drive type. The magnet assemblies and brush rings are attached to the gimbal housing, and the armatures are attached to the rotating gimbal components. The advantages of direct drive motors are:

- Low cogging torque and high frequency ripple virtually eliminate torque perturbations (and resulting tracking errors) caused by conventional motors. The ripple frequency is sufficiently high to avoid resonance.

- Zero backlash is achieved. The motors are secured directly to the gimbal, eliminating conventional drive components and their associated problems. Tracking accuracy is greatly enhanced, especially during particularly dynamic gimbal movements that would cause serious problems with conventional drives.

- Low mechanical compliance results in high fundamental vibration frequency. Wide servo position loop bandwidth becomes possible, allowing high responsiveness to external torque perturbations.

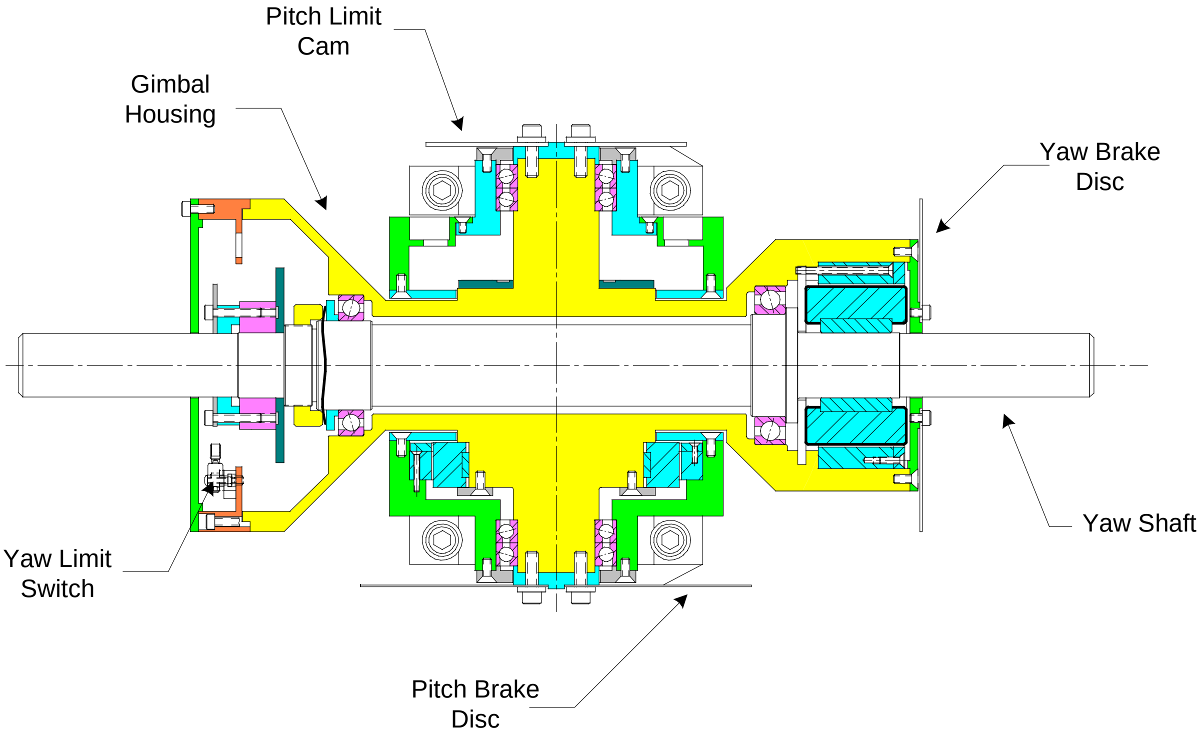

Figure 2. Section View Through Housing

7. Extreme Precision Incremental Optical Encoder

The optical encoders, like the motors, are direct drive type. The optical scale disks are mounted directly to the rotating gimbal components. The high torsional stiffness achieved with this method eliminates windup errors and greatly enhances gimbal accuracy. The disk however, must be mounted in a way that allows it to be centered about the shaft's axis of rotation.

The vast majority of direct drive encoder error is due to eccentric mounting of the encoder scale disk relative to the shaft's true axis of rotation. For instance, the yaw axis makes use of a shaft that passes completely through the housing, upon which is mounted the yaw axis encoder scale disk. This shaft is supported by precision angular contact bearings at each end, and therefore rotates about an axis. Due to bearing imperfections, the axis of rotation of the shaft does not exactly correspond to any physical feature. In other words, the axis of rotation exists, but it is impossible to find it by any conventional means. It is this elusive virtual axis that the encoder disk must be centered about

The output signal of the encoder is a 1-volt peak-to-peak sine function. Final resolution is achieved by interpolating that analog signal. The interpolation factor is programmable. Conversion of the interpolated signal to A-quad-B occurs in a small controller mounted on the side of the gimbal structure. Locating the controller as close as possible to the encoder sensing head minimizes the risk of EMI. The analog signal cable can be minimized to only a few inches in length. The encoder implementation is simple and robust.

The encoder accuracy for both axes was measured with an autocollimator and reference mirror. The results are shown below in Figures 3 and 4. For both encoders, the achieved accuracy is about .0045° peak-to-peak. Recall that the required accuracy is ± .005° (.010° peak-to-peak). Less than half of the error budget is consumed.

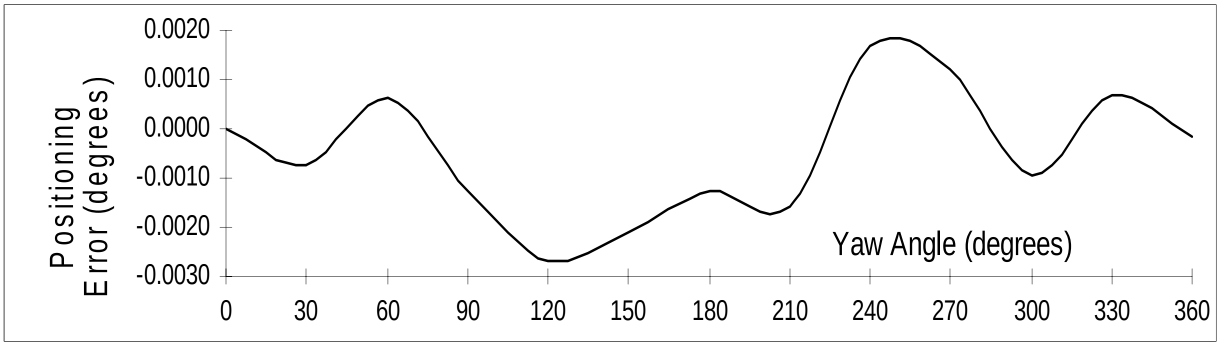

Figure 3. Yaw Axis Encoder Accuracy

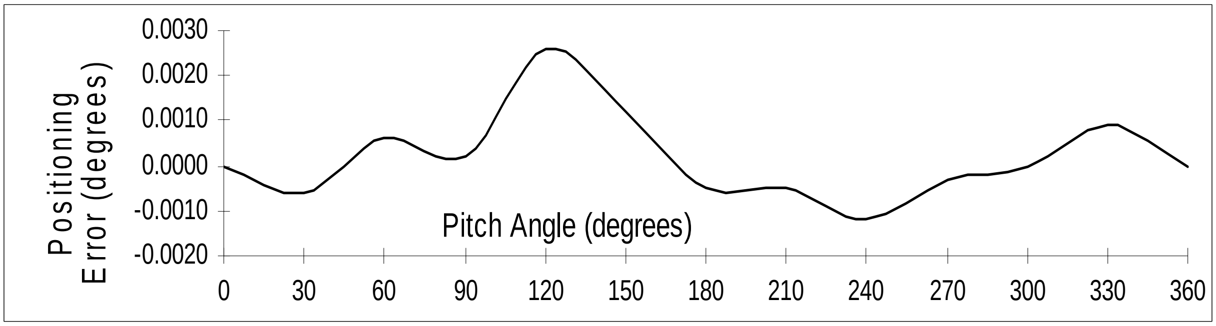

Figure 4. Pitch Axis Encoder Accuracy

8. Conclusion

The extreme accuracy tracking gimbal, when used in conjunction with its associated radome positioner, monopulse antenna, signal source, tracking receiver, compact antenna range, and servo control electronics provides reliable radome beam deflection measurements with an accuracy better than 0.1 milliradians rms.

This performance is enabled by a compact, structurally stiff, lightweight, and highly integrated gimbal mechanical design. Sophisticated direct drive motors, precision angular contact bearings, state-of-the-art encoders, and high bandwidth servos are employed to accurately track the RF beam.

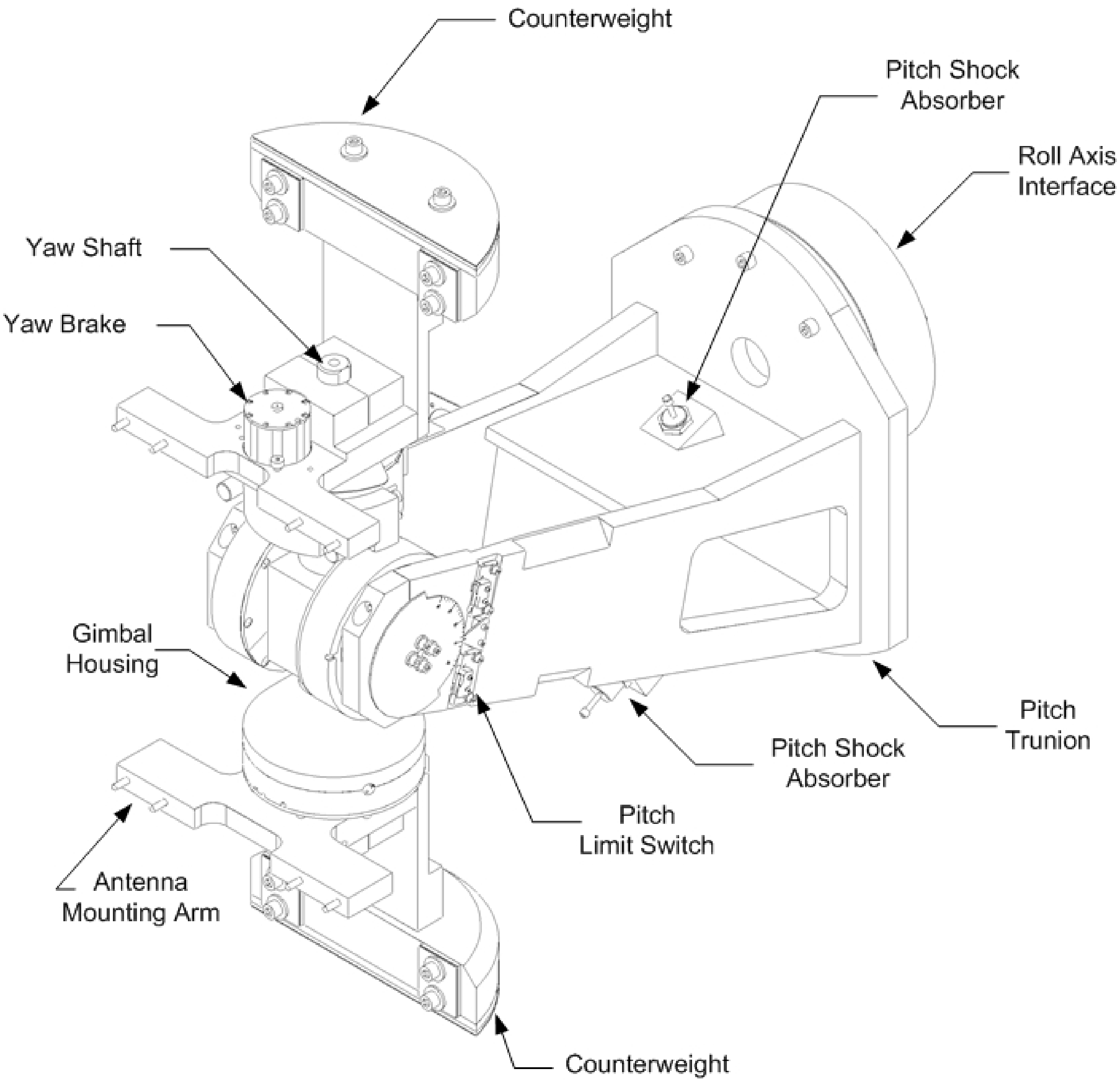

Figure 5. Extreme Accuracy Gimbal (Antenna Not Shown)