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A PRECISION BEARING GIMBAL SYSTEM FOR  
THE TEAL RUBY PROGRAM

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SUMMARY

The Teal Ruby Experiment employs a precision bearing gimbal system that allows it to stare at points on the earth while in orbit. This paper describes that gimbal system and points out problems encountered, analytical tools and test methods used, and data applicable to users of similar systems.

INTRODUCTION

The Teal Ruby Experiment (TRE) is an earth-orbiting infrared sensor. The TRE program is being carried out by Rockwell International Corporation, Space Systems Group. The program is sponsored by the Defense Advanced Research Projects Agency and managed by the Department of the Air Force--Headquarters, Space Division. The P80-1 spacecraft provides a stable orbiting platform for the TRE sensor.

The objectives of the TRE are (1) to demonstrate that cooperative aircraft can be detected from space with an infrared-type sensor, (2) to establish a global data base in several infrared spectral bands that will be useful in defining future space surveillance systems, and (3) to demonstrate, in space, mosaic infrared sensor technology.

The TRE sensor mosaic focal plane detects infrared energy radiated to space from the earth in several spectral bands. The focal plane and interior optics of the telescope are cooled to cryogenic temperatures by a solid cryogen system, which is integral to the sensor assembly. Three electronic boxes mounted on the P80-1 spacecraft functionally support the sensor assembly. Figure 1 shows the TRE mounted on the P80-1 spacecraft; figure 2 shows the sensor equipment arrangement.

The TRE has a pointing capability in both the in-track (line of flight) and cross-track axes of the sensor. The pointing control system, under direction of stored time-tagged commands, fixes the line of sight on an earth-fixed point by using spacecraft-supplied ephemeris, attitude, and angular rate data.

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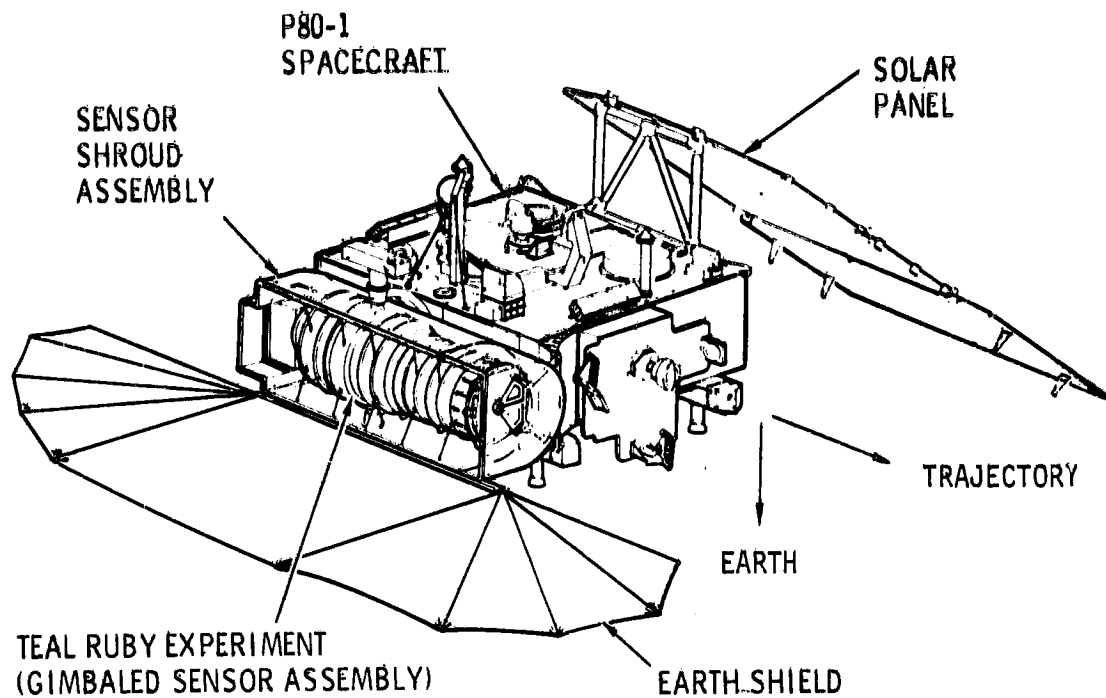


Figure 1.- Teal Ruby Experiment mounted on P80-1 spacecraft in stowed position.

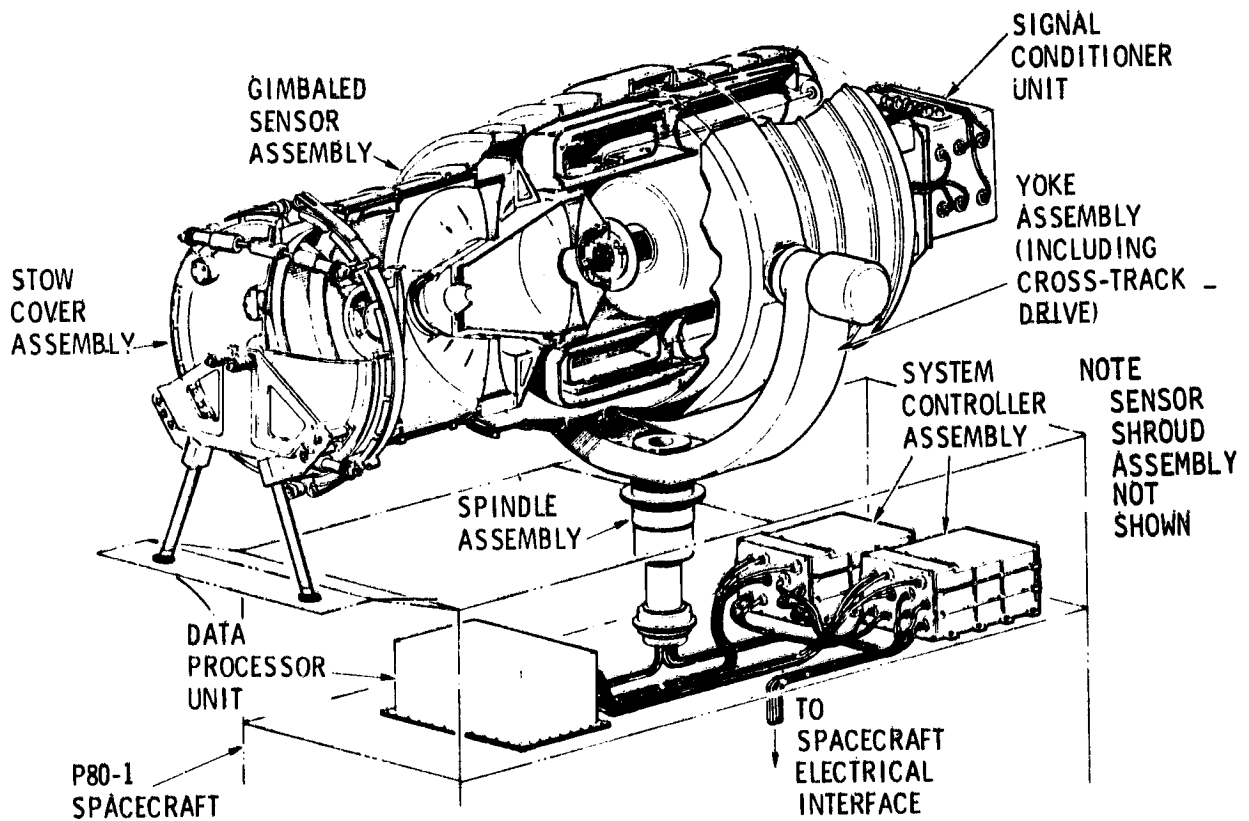


Figure 2.- Teal Ruby Experiment.

In the nominal "step-stare" operational mode, the pointing control system directs the experiment to stare at a ground point and hold that point fixed while the gimbal motion compensates for both spacecraft and earth motion. This stare operation may be repeated several times during a single data gathering period.

The TRE, mounted on the P80-1 spacecraft, is carried into low earth orbit by the Space Shuttle. After ejection from the orbiter payload bay, the spacecraft is boosted by the P80-1 propulsive stages to a final orbit altitude of approximately 740 km (400 nmi). Launch is scheduled for late 1981.

### GIMBAL SYSTEM REQUIREMENTS

The TRE gimbal system must meet stringent structural and dynamic requirements under varying conditions. Maximum loading occurs during launch and boost. To save weight, the spindle is allowed to deflect significantly under boost loads, but no bearing "Brinelling" or other roughness is tolerable that could result in excessive gimbaling noise during on-orbit operations. Minimizing the random noise content of the gimbal system is essential to avoid perturbing and obscuring the sensor data.

After the TRE reaches operational orbit, the gimbal system represents a relatively stiff mount for the sensor and is required to perform for a year with low torque and low noise, with significant temperature differentials across the bearings, and with bearing temperatures as low as 160 K.

To facilitate the step-stare operational mode, the sensor gimbal system must have two degrees of freedom through the excursion ranges necessary to accommodate the required field of view. Table I shows gimbal requirements in terms of excursions, torques, and accuracy. The 200-arc-second accuracy shown converts to a 0.7-km accuracy at a point on the earth's surface.

The torque budget is shown in table II for on-orbit operation. This table allocates the available torque from the motors into (1) torque used to move the sensor to its excursion extremes and (2) margin. The margin values include acceleration torque plus contingency torque to overcome any possible applied external loads, such as loads caused by loose insulation. Wire harness flexing may aid or hinder gimbaling, depending on the gimbal position at the time and the direction of travel.

### GIMBAL SYSTEM CONFIGURATION

The gimbal system arrangement is shown in figure 3. To enable the TRE to point at targets on the earth, the sensor is mounted on a gimbal system that provides two degrees of freedom for motion. This system consists of the following major components:

In-track spindle assembly

Cross-track trunnion assembly

Yoke structure assembly

Torque motor and resolver assemblies

Rate gyro assemblies

Bearing assemblies

The spindle assembly provides a low-friction rotating support for attaching the sensor to the spacecraft in a cantilevered fashion. The spindle is supported by two duplex, preloaded pairs of angular contact ball bearings. Spindle rotation is controlled with a motor-resolver assembly, rate gyro, and control electronics.

TABLE I.- GIMBAL REQUIREMENTS

Characteristic	In Track	Cross Track
Gimbal freedom (deg) operating	+80 to -60	$\pm 10$
Gimbal position (deg) stowed	-90	0
Gimbal rate (deg/s)	$\pm 1$	$\pm 1$
Motor torque, nominal (N·cm)	144	150
Pointing accuracy (arc-s)	200*	200*
Rate accuracy (arc-s/s)	0.52*	0.52*

\*Total P80-1/TRE budget

TABLE II.- TORQUE BUDGET

Torque Source	In Track (N·cm)	Cross Track (N·cm)
Bearing friction	21	14
Wire harness flexing	15	7
Margin	108	129
Total	144	150

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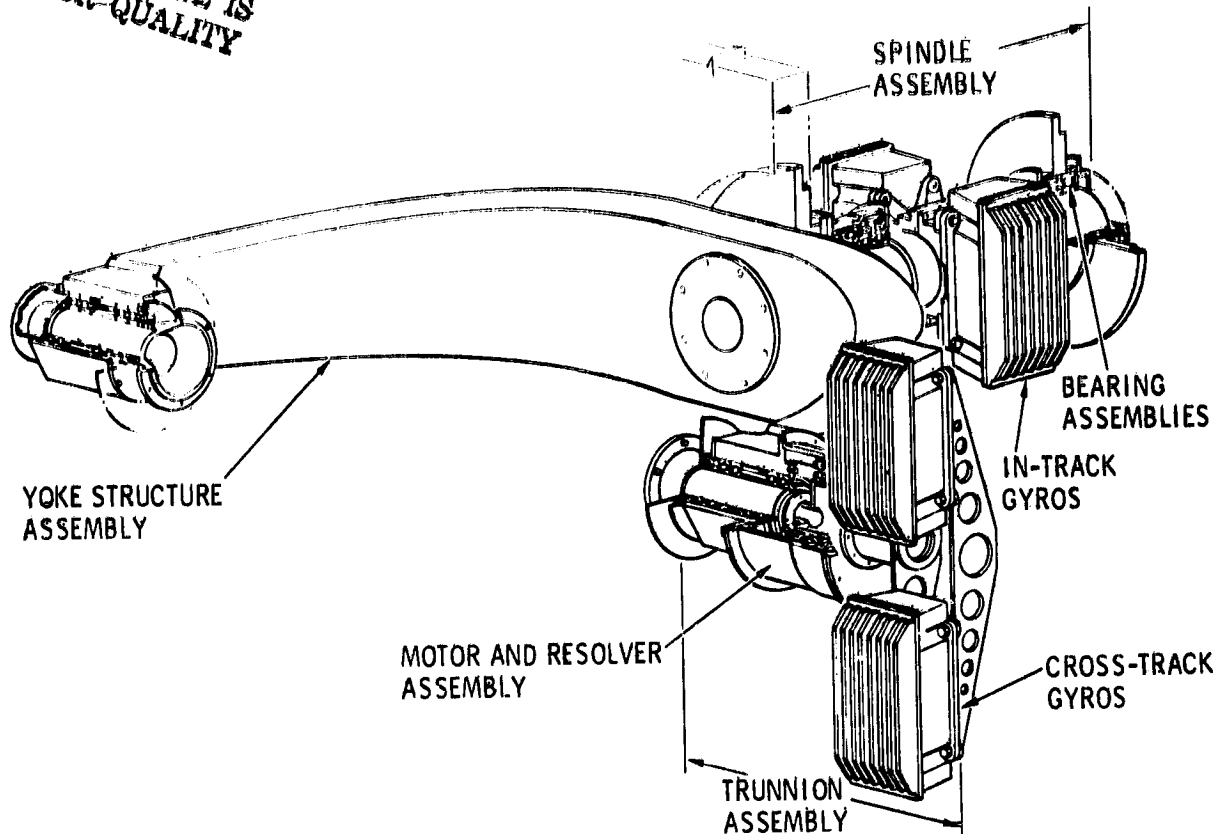


Figure 3.- Gimbal system arrangement.

The yoke is a U-shaped structure that attaches to the spindle at the base of the U. Trunnions extending from the sensor girth ring are accepted by cross-track bearings located at the ends of the yoke structure. This trunnion-to-bearing attachment of the sensor to the yoke provides the second degree of freedom for the sensor to enable cross-track viewing. Cross-track motion is similarly controlled with a motor-resolver assembly, rate gyro, and control electronics.

### GIMBAL SYSTEM DESIGN

Primary attention is given here to the design philosophy of the spindle system, which is similar to that of the cross-track system.

The spindle bearing installation in the outboard P80-1 attachment is shown in figure 4. The spindle, made from Inconel 718, is hollow in the center for wiring to pass through, interconnecting the P80-1 and TRE. The 90-mm internal diameter bearings are heated to 121°C (250°F) so that they can be slipped over the spindle shaft, then allowed to cool and contract there when properly positioned. Next, a lock nut is torqued up to apply a compressive load between the inner races. The outer races are clamped

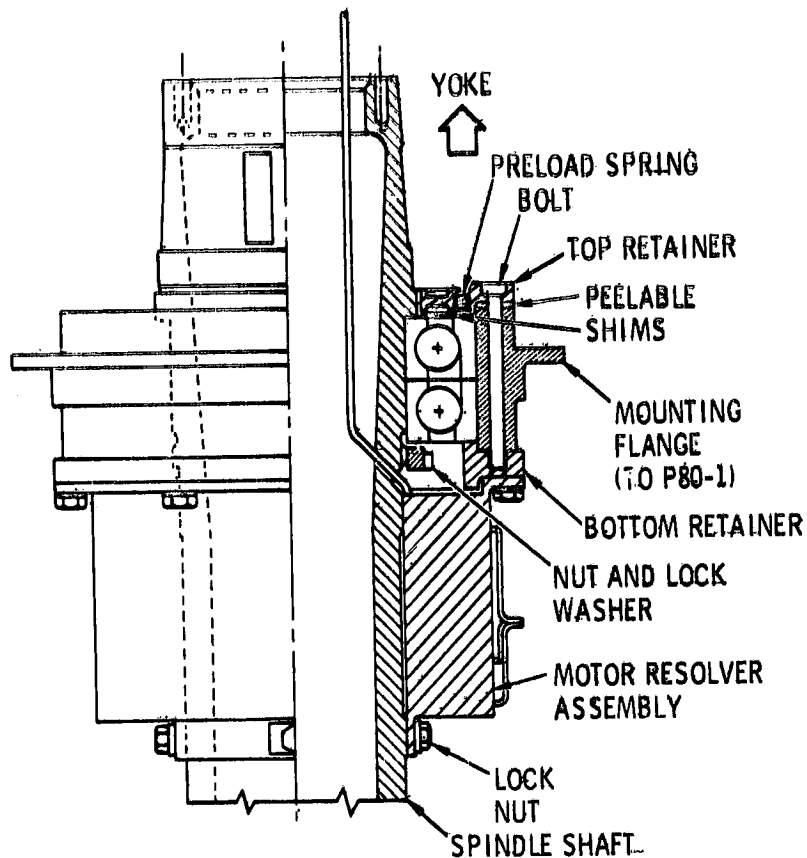


Figure 4.- 90-mm bearing installation.

between the top retainer, mounting flange, and bottom retainer. Peelable shims are positioned between the top retainer and mounting flange to control the maximum gap or interference between the outer races and the top retainer.

The design and dimensions of this installation limit looseness so that no "Brinelling" occurs during boost vibration. The maximum gap between the outer race of the top bearing and the top retainer is 0.0127-mm (0.0005-in.), and the maximum gap between the outer races and the mounting flange is 0.0102 to 0.0152 mm (0.0004 to 0.0006 in.).

On orbit, the spindle is cooled by its thermal proximity to the sensor body. Thus, the bearings shrink from their launch configuration dimensions and a looseness develops in the two areas mentioned above, allowing the outer races to "float." The preload springs now come into play to keep the prescribed value of 311 N (70 lb) on the bearings for smooth, low-friction operation during gimbaling.

The bearing installation in the inboard P80-1 location is shown in figure 5. It is similar to the outboard installation except that these bearings have an 80-mm internal diameter. No thrust loads are taken by the inboard bearings, and again the mounting flange freely floats relative to the outer bearing races after temperatures stabilize on orbit.

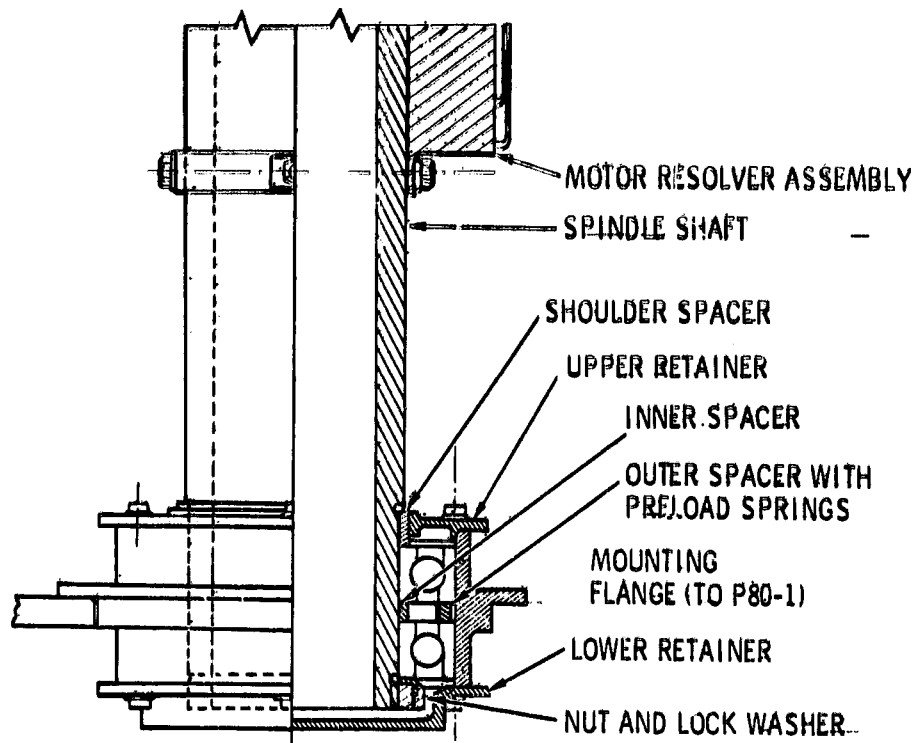


Figure 5.- 80-mm bearing installation.

The bearings themselves are of a precision design and are fabricated by the Fafnir Bearing Company for the TRE program. The material is 440C and the lubrication is applied by a unique process developed by Hughes Aircraft for spacecraft gimbal bearings.<sup>1</sup>

A dry lubricant was chosen to meet low-temperature requirements and to minimize outgassing. Similarly, a minimum thickness, maximum adhesion lubricant was needed to ensure low torque and noise. The lubricant system selected was molybdenum disulfide, applied by an RF sputtering process. The lubricant film thus applied is approximately 1200 angstroms thick. It is burnished and run in, and then the torque and noise are characterized.

#### ASSEMBLY

During assembly, parts are placed in their relative locations and allowed to "soak" to a constant temperature for 24 hours. Handling is minimized to avoid the effects of body heat and resulting expansion and distortion. All gimbal system assembly takes place in a 100,000-level clean room and assemblers wear lint-free gloves. Frequent use of a vacuum during assembly removes any loose dry lub or other contaminants.

<sup>1</sup>Christy, R.I., and Barnett, G.C.: Sputtered  $\text{MOS}_2$  Lubrication System for Spacecraft Gimbal Bearings. Hughes Aircraft Company,

The spindle was assembled several times at Rockwell to support various TRE and P80-1 tests. The recorded torque in the bearings varied significantly when measured at different times. Tests and analyses were conducted to build a data baseline and to identify significant contributors to increases in torque.

Early assembly activities revealed that the process of heat-shrinking the inner race of the bearings onto the spindle shaft did not greatly affect the bearing torque. There was a general increase in torque as a function of time, however, after the bearings were removed from their protective bags and installed. This effect appeared to be a combination of contamination and atmospheric moisture. There were also apparent contributions from asymmetrical loads induced by an accumulation of component tolerances and preload variations.

An example of how torque varied throughout the history of a set of 80-mm bearings is shown below. Bearing pairs were preloaded in all cases.

<u>Sequence</u>	<u>Torque (N·cm)</u>
1. As originally accepted at Fafnir (not installed)	4.2
2. Initial test at Aerospace Corp. (not installed)	4.9
3. Early installation on spindle	29-44
4. Repeat of test at Aerospace Corp. (not installed)	14.0
5. Flushed, dried, and reinstalled on spindle	7.3

An analysis of these data showed that the torque did not change significantly between sequence 1 and 2; a change of this magnitude could be attributed to different test setups. The change from sequence 2 to 3, however, was due primarily to a combination of (1) moisture and contamination plus (2) asymmetrical loads induced in installation. The effects of moisture and contamination were isolated by sequence 4, which tested the bearings in the same configuration as sequence 2. The difference in the sequence 3 torque (29-44) and the sequence 4 torque (14) was attributed largely to asymmetrical loading in installation. This anomaly was analyzed and corrected, and sequence 5 showed a return to low torque with installation discrepancies resolved--the bearings having been flushed and dried. Separate tests were run to further isolate the effects of preload, moisture, and contamination.



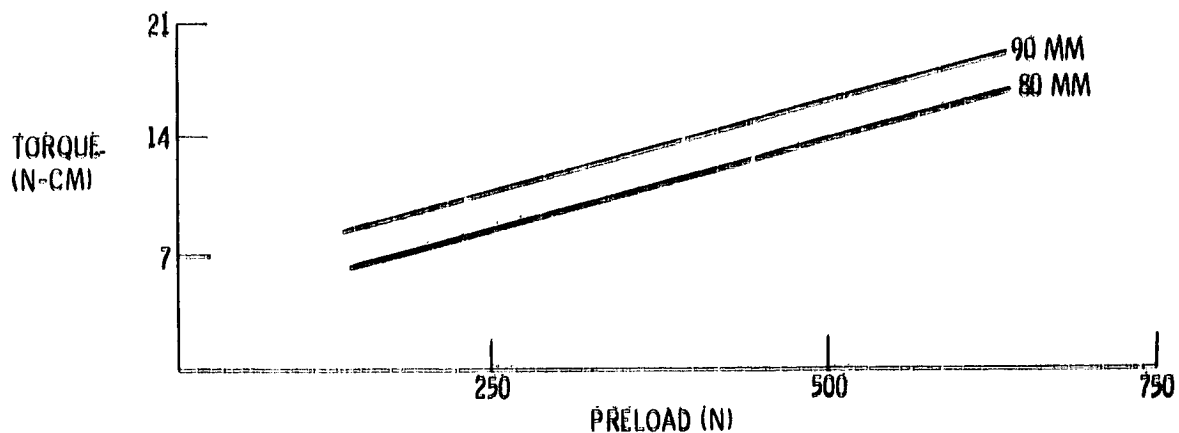


Figure 6.- Effects of preload on torque.

#### PRELOAD TESTS

Since assembly tolerances can cause excessive bearing preload, it was necessary to determine and understand the effects of preload on bearing torque. Tests were run on the 80-mm and 90-mm bearings immediately after cleaning and drying. The results, shown in figure 6, indicate a linear increase in torque as a function of preload within the range tested. Nominal preload provided by the springs is 245 N (55 lb) for the 80-mm bearings and 311 N (70 lb) for the 90-mm bearings. These data were used in analyzing the relative contributions of assembly variations.

#### MOISTURE TESTS

The effects of moisture and contamination were of primary interest because they could become extreme as a function of time and usage prior to launch. A series of tests was conducted to isolate the contribution of moisture. The following sequence of activities took place under controlled test conditions.

1. Install bearings on a spindle; run baseline torque tests.
2. Expose spindle to 85-percent relative humidity for up to eight days, conducting intermittent torque tests, until torque reaches a constant level.
3. Bake out spindle in a dry oven at 121°C (250°F) until torque reduces to a constant lower level.

The data from these tests indicate the maximum and minimum torque to be expected from a set of bearings with maximum and minimum moisture.

A related test series was then conducted to determine if bearings dry out in a space environment.

1. Conduct baseline torque tests.

2. Reintroduce moisture as in step 2, above.
3. Install spindle in a vacuum chamber and control bearing temperature to approximate on-orbit levels.
4. Conduct torque tests after prescribed time increments to verify torque reduction to budget levels.

These data dictate the degree to which atmospheric moisture can be tolerated in the bearings prior to launch and, conversely, the degree of protection required to minimize moisture accumulation. The data from these tests are being evaluated and will be presented at the symposium.

#### STRUCTURAL ANALYSIS AND TEST

Analysis of the gimbal assembly from a structural standpoint was initiated early in the design. The spindle assembly in its cantilevered loading condition was the most critical area of analysis; and the bearings were identified as the most critical structural elements within the assembly.

Rockwell used a unique program to predict bearing stresses for both rigid and flexible spindle shaft and housing. Parametric analyses gave insights into the sensitivity of bearing stresses to such factors as element stiffness and installation misalignment.

Load tests were conducted with the spindle installed on the actual flight spacecraft. Limit loads were applied to the spindle in three axes. To pass this test the spindle assembly had to remain undamaged, and bearing noise had to be within prescribed limits. After the spindle was loaded in this static test, the bearings were removed, and the total assembly was inspected. No discrepancies were noted, and bearing noise did not increase from the pretest levels.

The test was then repeated at 1.25 times limit loads. The criterion for this test was that no permanent deformation could occur; there was no noise criterion. The assembly passed the test, but the bearing noise did increase above the level allowed in the noise budget.

#### NOISE TESTING

An essential element in minimizing data disturbances induced by the sensor itself is control of the noise sources that cause line-of-sight jitter. One of the sources of noise that must be monitored and controlled is roughness in the gimbal bearings from contamination, chipped dry lube, "Brinelling" of the balls and races, etc.

Before and after vibration and static load testing, noise tests were run on preloaded sets of bearings. Basically, a sensitive torque test was conducted while the bearings were rotated several times. The torque data were then run through narrowband filters to determine the energy level in the noise versus frequency. These data were then used

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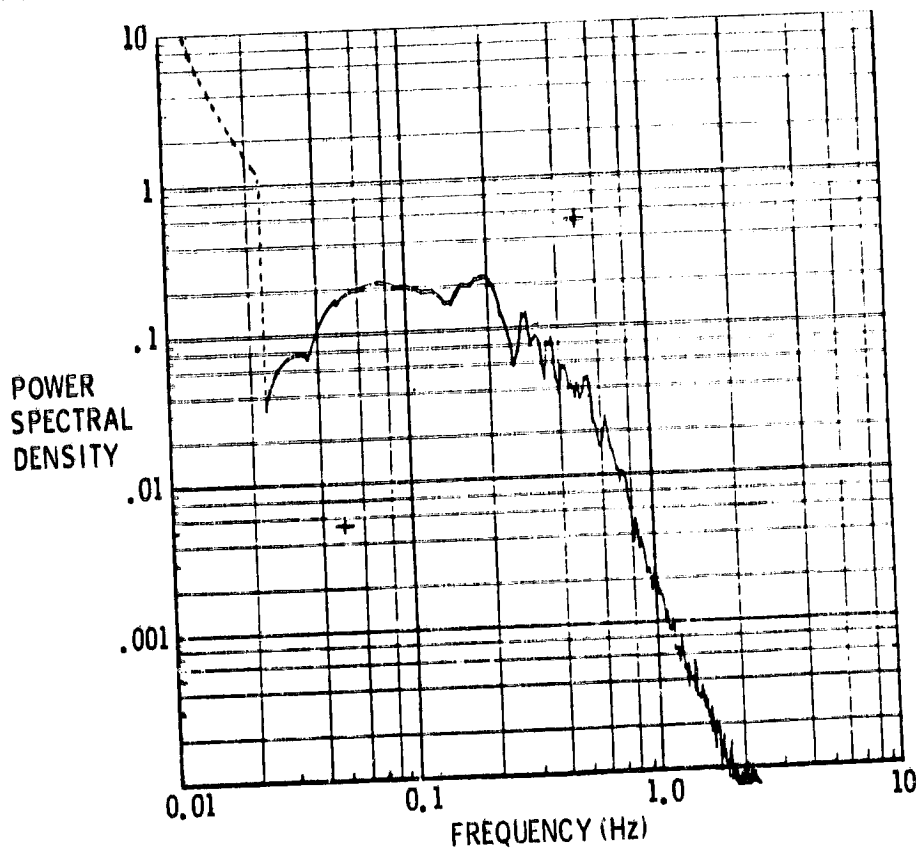


Figure 7.- Bearing noise.

in the TRE servo dynamic math model to verify that the resulting line-of-sight jitter was acceptable. Figure 7 shows a typical power spectral density plot for the 90-mm bearings.

Noise testing on the Teal Ruby program verified that qualification-level random vibration and limit-level static loads do not appreciably affect noise, but bearing contamination increases the noise level significantly.

#### CONCLUDING REMARKS

Proper use of contemporary design principles and fabrication techniques can produce a gimbal system capable of supporting a precision-pointing, low-weight, low-noise sensor. Cleanliness, moisture control, and control of component tolerances are essential to minimizing adverse effects.