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Space Telescope Fine Guidance Sensor Bearing Anomaly /125116

S. Loewenthal[*], J. Esper[**], J. Pan[+] and J. Decker[++]

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Abstract

Early in 1993, a servo motor within one of three Fine Guidance Sensors (FGS) aboard the Hubble Space Telescope (HST) reached stall torque levels on several occasions. Little time was left to plan replacement during the first servicing mission, scheduled at the end of '93. Accelerated bearing life tests confirmed that a small angle rocking motion, known as Coarse Track (CT), accelerated bearing degradation. Saturation torque levels were reached after approximately 20 million test cycles, similar to the flight bearings. Reduction in CT operation, implemented in flight software, extended FGS life well beyond the first servicing mission. However in recent years, bearing torques have resumed upward trends and together with a second, recent bearing torque anomaly has necessitated a scheduled FGS replacement during the upcoming second servicing mission in '97. The results from two series of life tests to quantify FGS bearing remaining life, discussion of bearing on-orbit performance, and future plans to service the FGS servos are presented in this paper.

Background

In April of 1990, the HST was launched into Low Earth Orbit (LEO) aboard the space shuttle Endeavor. Soon after launch, it became apparent that the required HST pointing precision could not be achieved due to the presence of thermally-induced jitter originating from the large, flexible HST solar arrays. In addition to the jitter problem, HST operations were compromised by spherical aberration in the HST primary mirror, the presence of which was confirmed several months after HST deployment. Plans were drawn up to conduct a servicing mission to remedy these problems. Periodic servicing of the HST using the space shuttle is necessary, and is possible because the HST is in LEO and designed to facilitate such on orbit servicing. The HST First Servicing Mission (FSM) occurred in December of 1993, and achieved the goals of correcting the solar array jitter and spherical aberration.

In the period prior to the FSM, HST operations were tailored to achieve the best possible science in spite of the operational problems noted above. To that end, the FGS's aboard the HST were operated in a manner which helped improve the HST pointing performance, but did so at the cost of incurring degradation within the Star Selector Servo (SSS) ball bearings. As will be presented, FGS bearing degradation in general has been strongly correlated with a "Coarse Track" mode . During the first three years of HST orbital activities, this mode was implemented due to its robustness in maintaining star lock during strong disturbance periods caused by the thermal "snapping" of the now replaced solar arrays. In CT, the servo bearings rock back and forth ± 0.75 degree or less for extended periods, causing depletion of the oil under the

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[*] Lockheed Martin Missiles and Space Co., Sunnyvale, CA
[**] Allied Signal Technical Services Corp., Columbia, MD
[+] Space Telescope Science Institute, Baltimore, MD
[++] NASA Goddard Space Flight Center, Greenbelt, MD

ball contact and inhibiting oil replenishment. At a frequency of 1 Hz, tens of millions of CT cycles were accumulated causing degradation of the Bray 815Z oil in the contact and the formation of lubricant debris (friction polymer).

The presence of this degradation became apparent early in 1993, when HST telemetry revealed instances of high torque in one of the FGS bearings. In fact, the excessive torque occurrences resulted in operational interruptions and some loss of HST science observations. Torque levels of the bearings in one of three FGS's on-board HST, reached motor saturation levels of approximately 10 volts equivalent servo torque (1 volt ≈ 46 N-mm or 6.5 oz-in) as shown in Fig. 1 (see early '93 time frame). Although temporarily stuck, subsequent operations freed it. This anomalous bearing behavior led to the investigation outlined in this paper.

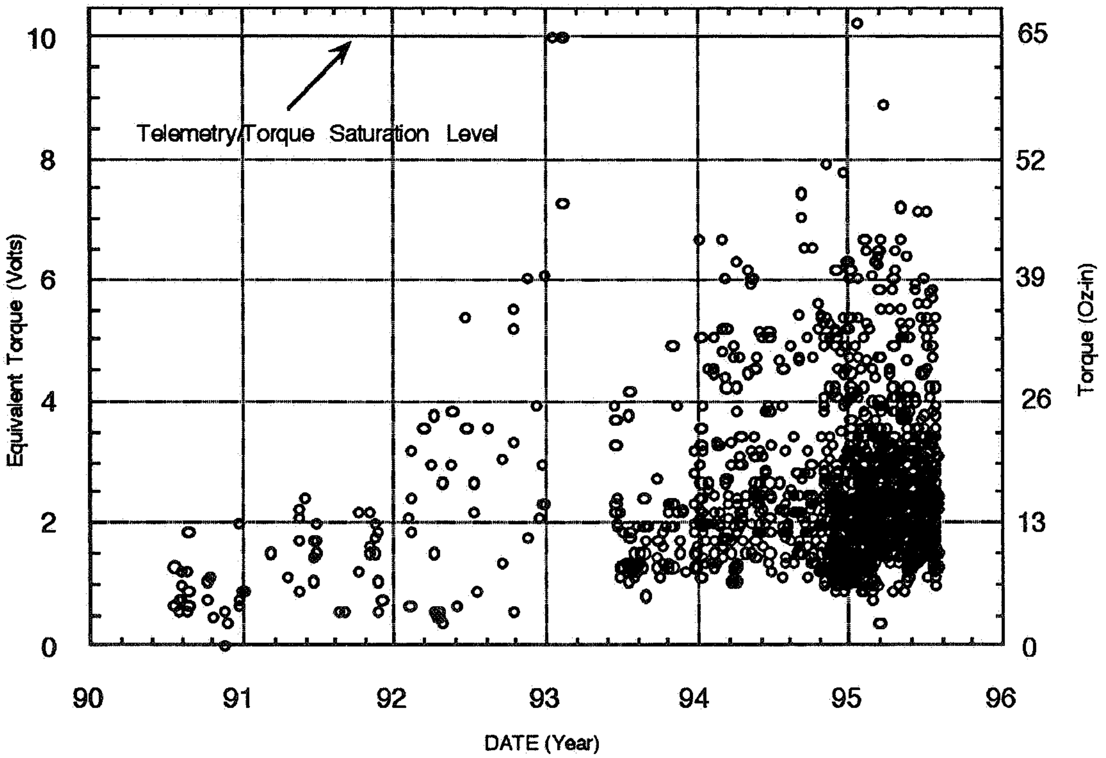


Figure 1 - FGS 2A Torque history from launch. Note motor torque saturation in early '93 and then temporarily recovers with change to Fine Lock operation.

Fine Guidance Sensor Description

The Fine Guidance Sensors are electro-optical, interferometric instruments used to lock and track target stars. About the size of baby grand piano (Fig. 2), the FGS is perhaps the most precise pointing system ever built. It is capable of holding 0.007 arc secs of pointing accuracy over a 24 hour period; equivalent of targeting a dime over 400 km. At the heart of the FGS is the bearing-motor-encoder system which positions optics inside the SSS assemblies (Fig. 2).

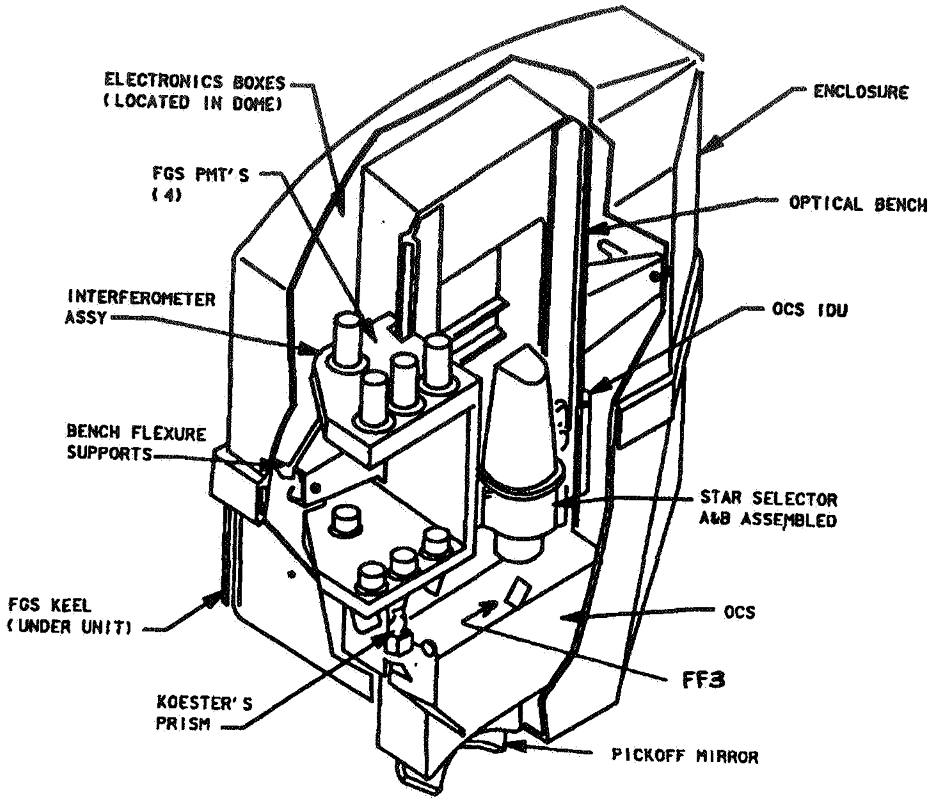


Figure 2 - FGS optical and mechanical arrangement showing Star Selector Servo location.

Operation - The FGS operation consists of comparing guide star intensity measurements so as to achieve a prescribed amplitude level at each of four Photo Multiplier Tubes (PMT). The intensity at each PMT is in turn dependent on the amount of wave front tilt falling onto the Koesters prisms within the FGS optical train, illustrated in Fig. 3. Initially, a combination of spacecraft and FGS optical element motion will set the intensity levels within a range for which "lock" is defined. Once the FGS is locked onto the target, any deviations will be quickly corrected by repositioning the spacecraft in order to maintain the target on axis (zero wave front tilt).

As shown in Fig. 3, the light from the HST primary mirror is intercepted by the FGS pickoff mirror and channeled through the Star Selector Servo "A" and "B" assemblies. These SSS assemblies can be moved independently of each other to affect the tilt of the wave front onto the Koesters prisms. The centerpiece of each SSS assembly is a 21-bit encoder, brushless DC motor supported in large, thin section angular contact ball bearings.

Target Star Acquisition - In order to achieve lock in the first place, the FGS must go through a target star acquisition process. The SSS assemblies optically positions a 5 arc-second-squared, Instantaneous Field of View (IFOV) onto a 60 arc-minute-squared, Total Field of View (TFOV) (see Fig. 4). Hence, by moving the SSS assemblies about their rotation axes, the IFOV can be maneuvered anywhere in the TFOV. Briefly, the SSS is slewed *(#58 command)* to the start of a *spiral search* pattern, where the angles oscillate at increasing amplitudes, reaching a maximum amplitude of about 2 degrees (4 degrees full stroke). Following this is a brief period of Coarse Track (CT) oscillations, where the target is initially acquired prior to transitions to either Fine Lock (FL) or CT operations (described next). In the case when the system transitions into FL, a second slew *(vehicle offset)* is carried out to position the astronomical target at the science aperture. To provide a realistic ground test, these modes of operation were emulated during the second of two series of bearing life tests.

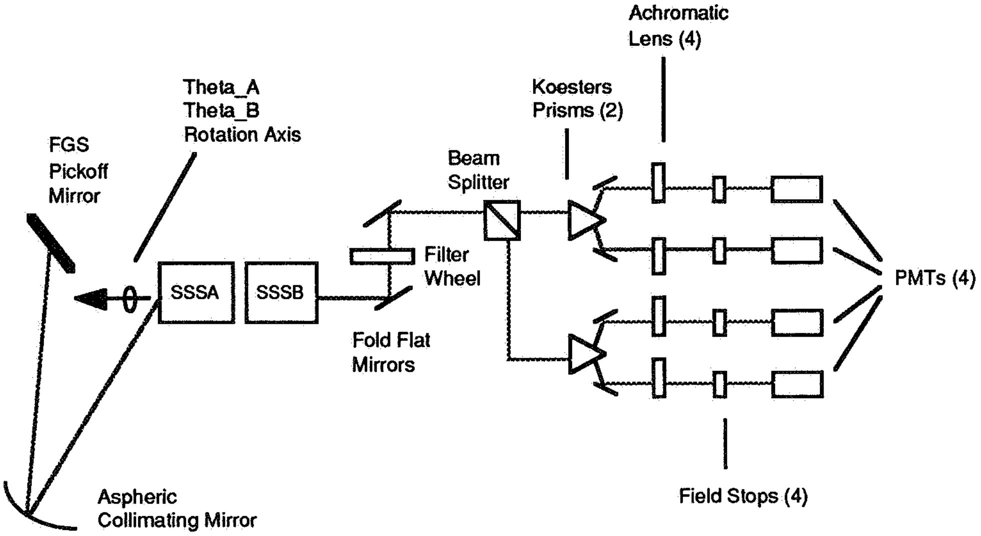


Figure 3 - FGS optical train showing optical path through SSS A & B assemblies and Koesters prisms to PMT's

Coarse Track and Fine Lock - The tracking operation begins once the target star has been locked on. There are two different tracking modes: Coarse Track (CT), and Fine Lock (FL). These two operational modes have the greatest impact on long term FGS bearing life. During CT operation, the IFOV is made to nutate about the center of light of the target star. This nutation cycle is accomplished by oscillating each SSS about their rotation axes with an amplitude of approximately ±0.75° or less, forming the elliptical pattern appearing in Fig. 5. The life tests were geared toward simulating the CT mode of operation, the suspected cause of SSS bearing degradation.

On the other hand, FL operation does not involve any SSS nutation, but rather the IFOV is held relatively fixed at the target star. The only motion is the result of spacecraft jitter, generally less than ± 10 arc-seconds of SSS rotation. FL operation with its microscopic SSS motions were not considered to contribute to bearing degradation, since the resulting bearing ball motions were believed within the elastic (Dahl friction) regime. This too was to be proven by the bearing ground test.

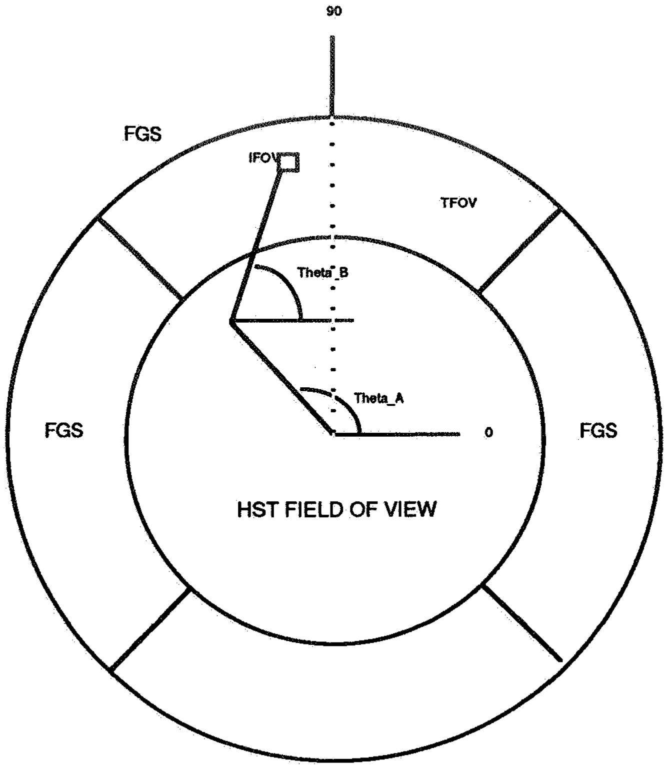


Figure 4 - FGS Field of View showing both SSS "lever arms" (A and B) in terms of corresponding servo (rotation) angles, Theta_A and Theta_B

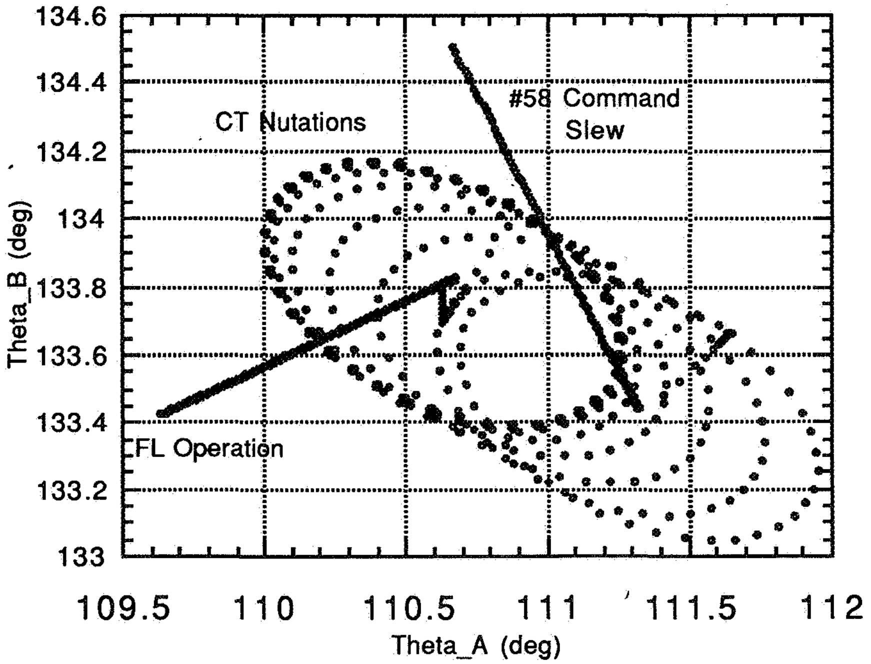


Figure 5 - Coarse Track nutations during a guide star acquisition (spiral search is negligible in this case)

Anomalous Flight Data

As a result of the millions of CT cycles accumulated, all FGS bearings exhibited anomalous torque spikes or bumps at various times during their operational use. However, only the bearings from the FGS 2A servo showed serious degraded performance. Although such events may occur at other times, there are three occasions where their appearance have been trended over time to monitor bearing health: during a #58 slew, during a vehicle offset, and during "rate reversals". The latter is a "target acquisition" maneuver in the reverse direction during a vehicle offset slew. This reversal manuever has recently shown to be a problem for FGS 1B.

As illustrated in Fig. 6, high torque is consistently observed in FGS on-orbit data when a FGS bearing slews past the its end of CT stroke position. Of the 6 SSS's, the CT bumps appear largest in Servo 2A and smallest in Servo 2B. The torque magnitude of a CT bump is, on average, proportional to the duration of CT operations. The longer a CT operation lasts, the bigger a resultant CT bump until some limit is reached. This limit value grew with mission time, causing the anomalous torque observed in Fig. 1.

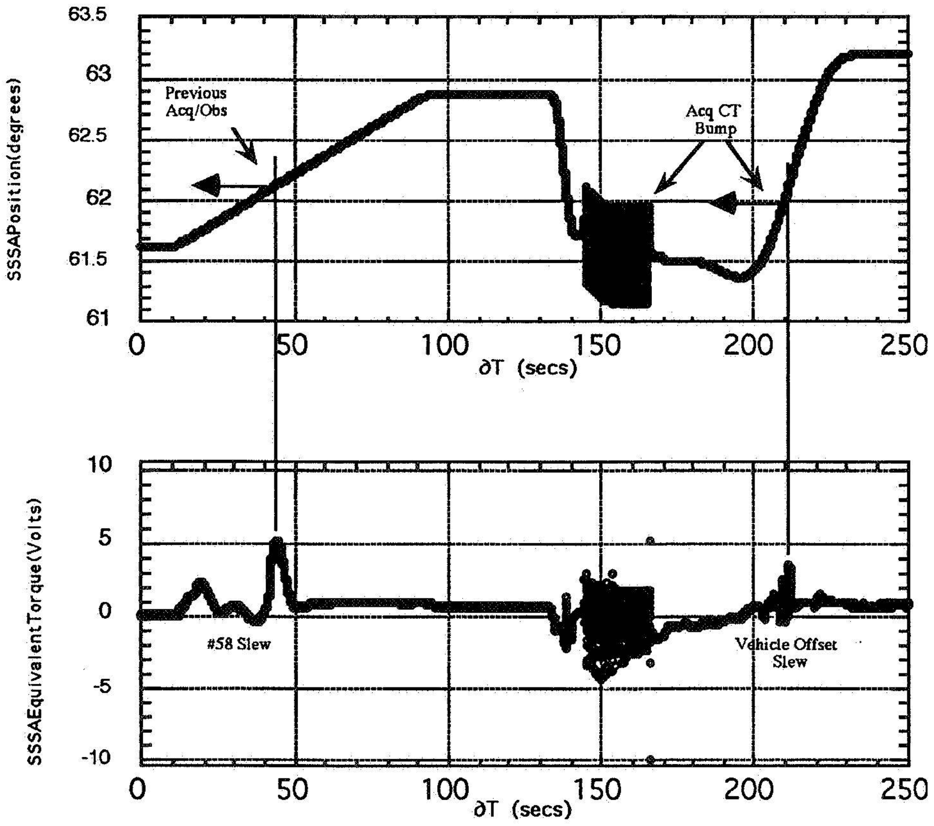


Figure 6 - Correlation of torque bumps with bearing operations. Notice that torque bumps (bottom) correspond to end of CT stroke at ≈ 62 deg (upper)

From telemetry data it appeared that the CT bump heights (torque) were sequentially reduced as balls compressed them during a slew. Rather than hard impediments, it suggested that a CT bump resulted from the balls running over some kind of debris ridges that had accumulated along the bearing races and perhaps the sides of the balls during the limited back-and-forth motion of each ball in CT operation.

First Bearing Life Tests

Two series of accelerated bearing life tests were conducted to investigate the problems observed on orbit. The first of these was conducted shortly before the first servicing mission in December of 1993. It was crucial to have results as soon as possible to support a replacement decision for FGS 2A, the most degraded servo. The previously unplanned replacement of this FGS represented a major addition to the servicing mission, which was already pushing the limits for EVA time and little training time remained for the SSTS crew to practice such a replacement. The key goals of the test were to: (a) determine the likely remaining life of the FGS bearings, (b) assess life benefits from minimizing CT operation in favor of FL operation, believed more benign and (c) identify the likely failure mechanism.

Test Conditions - The first life tests consisted mainly of Coarse Track motion, the primary suspected cause of accelerated lubricant degradation and subsequent debris related torque bumps. While long periods of dithering motion over the same spot on the bearing is difficult for any oil, it is particularly troublesome for the Bray 815Z , a perfluorinated ether oil, which contains no protective boundary lubricant additives.

It was estimated that approximately 21 million ±0.75 deg CT cycles were accumulated at the time of FGS 2A failure, some 33 months after launch. To obtain test data quickly, the first 3 years of the FGSs' primarily CT operation were compressed into 13 test weeks by accelerating the CT frequency from 1 Hz to 3.5 Hz and eliminating idle time. This acceleration factor still maintained the bearing's boundary mode of lubrication and expected wear out failure mode Also to save test time, the test excluded other FGS slew modes, which contributed little to the bearing problem. However, periodic 0 to 40 to 0 deg #58 command slews were simulated every 19,000 cycles, since these help redistribute the debris and re-wet the contact.

The second phase of the tests were to evaluate the expected life that could be obtained with FL operation. Hopefully, the primary use of FL would enable FGS 2A to operate until the second servicing mission, scheduled some 3 years later. During FL, the bearings "strain" through a very small angle (< 10 arcsec) to compensate for the small amount of spacecraft jitter caused by the reaction wheels, solar arrays and any other contributing sources. This small motion was expected to be primarily in the elastic range of the bearing before breakaway (so-called Dahl regime) and below that resulting in fretting damage. It was estimated that ± 12 asec stroke would envelope the worst case displacement observed during the first 3 years of service. Projected usage indicated that an additional 160 million cycles of FL would be accumulated before the second servicing mission. A FL cycle rate of 16 Hz would permit completing the test in less than 20 weeks.

Test Bearings - In the flight servos, each bearing assembly consisted of a pair of class 7+, thin-sectioned, 25 deg angular contact ball bearings mounted in Beryllium structure, separated by 3.6 cm long, inner and outer preload spacers and hard preloaded in a back-to-back configuration. These bearings were designed to provide maximum stiffness and precision in supporting the servo's 21-bit encoder and, as a consequence, were unusually torque sensitive to lubricant debris and thermal gradients.

Off-the-shelf angular contact ball bearings were fortunately available that closely matched the flight bearings' geometry, except that the test bearing's contact angle was 30 instead of 25 deg and the PTFE alternating ball toroids were about 2/3 the thickness of the flight bearings' toroids. To assure a conservative test, an oil charge of 100 mg of Bray 815Z oil was used, instead of the flight's 375 mg, in order to help compensate for the flight bearings' losses during the 7 years of storage and 3 years of orbital time. A trycrysl phosphate (TCP) pre-coating on the races was used in keeping with the flight bearings. The flight and test bearings were both made from 440-C steel, had bore diameters of 165mm (6.5 in), outside diameters of 190 mm (7.5 in) and contained 88 balls of 4.8 mm (3/16 in diameter per row. The bearings were hard-preloaded to 670 N (150 lb), producing a relatively low, maximum Hertz stress of 0.83 GPa (120 Ksi).

Test Rigs - Lockheed's computer controlled, turbo-vacuum pump bearing life test rigs were used for the CT life tests. Vacuum levels of 10^{-6} to 10^{-7} torr and temperatures of 20 to 22°C were maintained to simulate on orbit conditions. The FL tests required the construction of a special 4-bar, bell-crank mechanism that could accurately impose the desired ± 12 arc sec motion. The motorized bell crank reciprocated a linkage attached via flex pivots (no dead band) attached to a crank arm coupled to the inner race of the test bearing. A proximity probe measured bearing rotation angle while a load cell monitored bearing torque.

CT Results - Both test bearings showed evidence of high torque after CT cycling near the 20 million cycle point. This, coincidentally, was about the same number of CT cycles accumulated by the FGS 2A bearing when it began to get stuck and of similar torque magnitudes. Torque levels of 424 N-mm (60 oz-in) or greater were recorded when the bearing was slewed past the end of CT motion, designated by torque bump spacing on the order of 2 degs in Fig. 7. Debris primarily from degraded lubricant, piles up at the end of the CT stroke creating a barrier for the ball to roll over. This end-of-stroke debris location closely corresponds to the theoretical ball spacing of 8.9 degs, labeled between the start of the large torque bump and the following one in Fig. 7. Careful disassembly of the bearing clearly show debris ridges at regular ball spacing as shown in Fig. 8. Telemetry data from the flight bearings also showed similar end-of-CT stroke spacing for the torque irregularities.

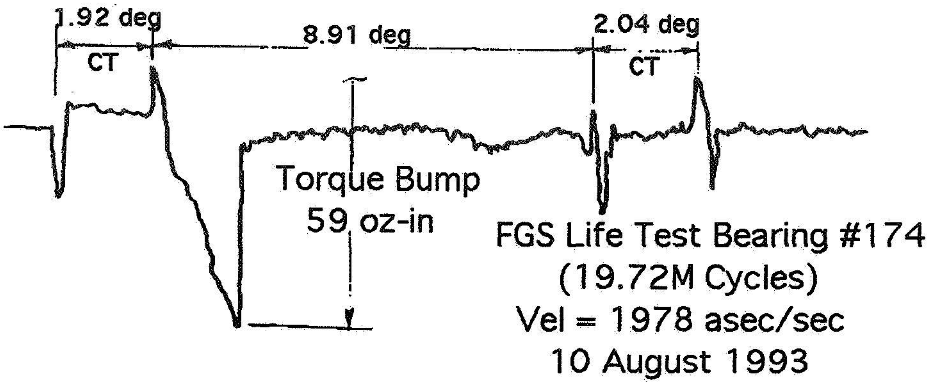


Figure 7 Torque Bump Trace for Test Bearing at 19.7M Cycle, showing Bump Spacing at CT End-of-Stroke Locations

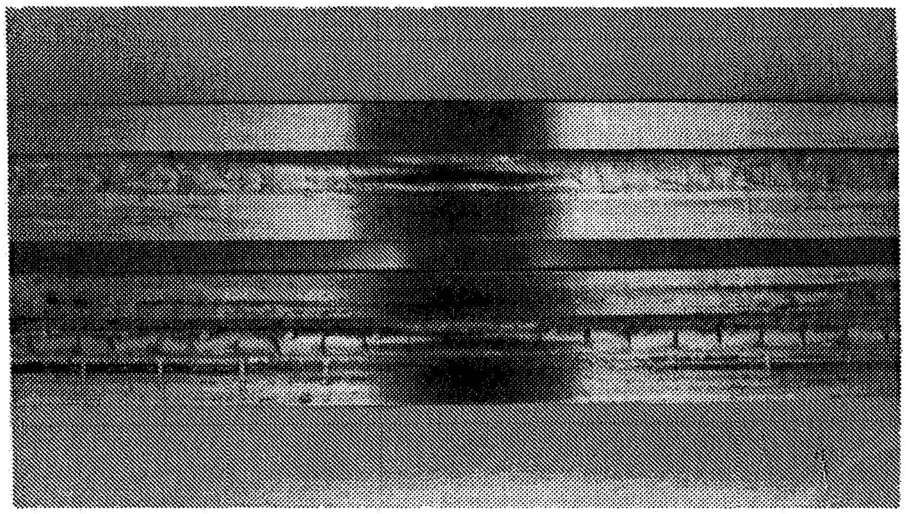


Figure 8 - Debris Ridges Observed at Ball Spacing Intervals on Post Test Disassembled Bearings

<u>FL Results</u> - No noticeable change in torque signature was observed for the test bearing receiving 178 M cycles of FL after it had already been exposed to nearly 35 M CT cycles as shown in Fig. 9. To confirm these results, a second, but virgin, test bearing was tested to 105M cycles of FL and it too exhibited no detectable degradation.

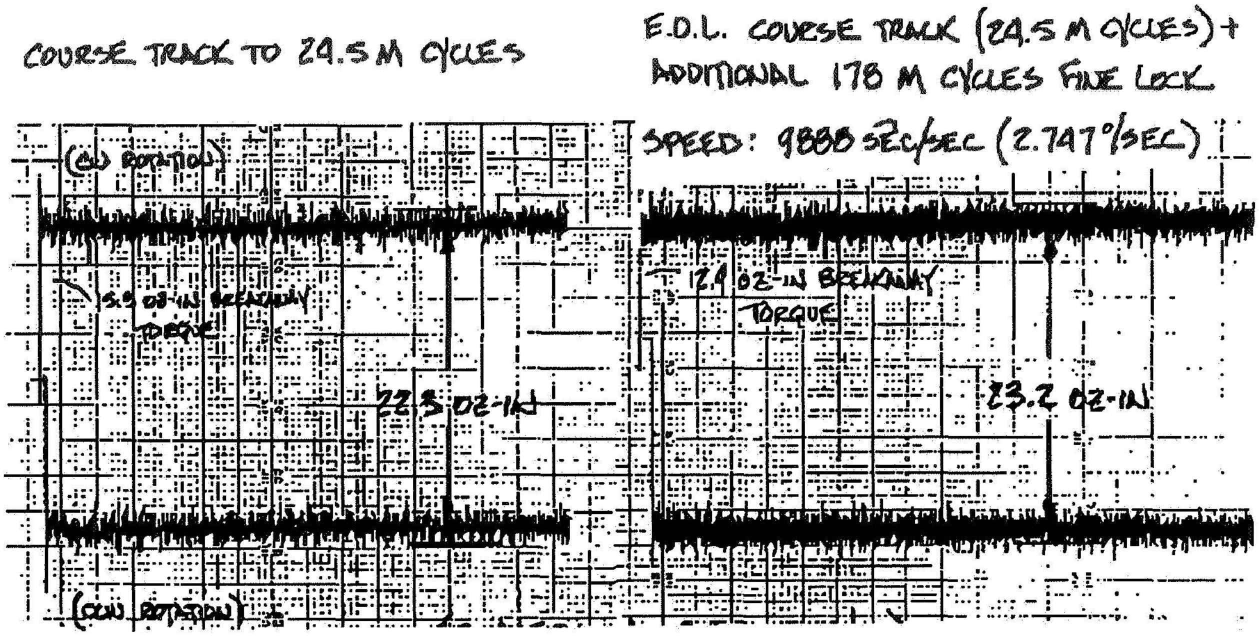


Figure 9 - Bearing torque signature showed little change after 178M cycles of Fine Lock dithering after previously receiving 35M cycles of CT.

Second Bearing Life Tests

On the basis of the results from the first set of tests, a change in operation to primarily FL operation (>90%) was uploaded to the flight FGSs in the April 93 time frame. A marked decrease in FGS 2A torque was observed (Fig. 1) and a decision not to replace the servo for the December repair mission was made. However, the question remained as to how long this and the other servos would continue to last with the normal modes of operation which still include some CT operation. Furthermore, could replacement be avoided again during the second servicing mission, scheduled for in the spring of '97.

A second set of life tests were planned. These tests had greater fidelity in emulating the various modes of on-orbit operation and simulating bearing life far into the future, up to the 4th potential service mission in the year 2002. Unlike the first set of tests conducted in only a few months, the acceleration factor would be reduced to nearly unity and the test bearings would be "identical" to the flight ones in all aspects. Another objective was to evaluate the effectiveness of current on-orbit trending techniques and to establish the benefits, if any, of periodic maintenance slews on the recurrence of torque bumps. A final goal was to quantify life improvements with an "improved" bearing design for a future FGS replacement. This bearing maintained the same geometry as the flight bearings to facilitate replacement, but a more wear resistant Neopentyl Ester (NPE) oil containing a boundary lubricant additive (TCP) was substituted for the Bray 815Z. Also the ball toroid thickness was slightly reduced to provide a little more clearance than the flight unit. This time all test bearings were lubricated with the flight charge of 375 mg of oil.

Duty Cycle - The test duty cycle was divided into two parts. The first part "aged" the two "flight" bearings using the same CT intensive operation that was in effect for the first 37 months of flight (23 million cycles). The 4 FGS motion modes (vehicle offset, #58 command, spiral search and coarse track), as described earlier and defined in Table I, became part of the test profile.

Table I - Test Profile

First 37 months of Flight 4/90 - 6/93 (23M CT Cycles)

Motion Type	Direction	Angle deg	Rate deg/sec	Cycles
Continuous (Veh Offset)	CCW	8	1.112	1
Continuous (#58 com)	CW	30	1.868	1
Gimbal (Spiral)		± 1.92		10
Gimbal (CT)		± 0.65		2301

Next 110 months of Flight 6/93 - 9/02 (30M CT Cycles)

Motion Type	Direction	Angle deg	Rate deg/sec	Cycles
Continuous (Veh Offset)	CCW	11	1.11	1
Continuous (#58 com)	CW	42	1.43	1
Gimbal (Spiral)		± 1.16		4
Gimbal (CT)		± 0.44		249

Special Profile (4-Rev Test)

Speed deg/sec	Direction	Revs deg
1.87	CW	1
1.87	CCW	2
0.55	CCW	1

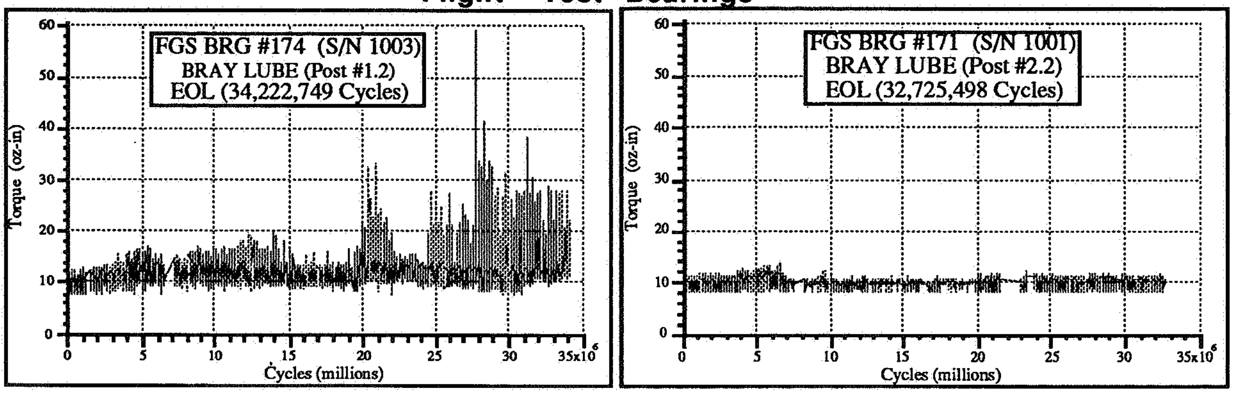
The second part of the test exposed the test bearings to the current Fine Lock (FL) intensive operation for the next 8 years (to 2002). During this period another 7 million additional CT cycles was expected to be accumulated, representing just 10% of the past CT usage rate. Actual Fine Lock operation was eliminated from the test profile since it produced no detectable degradation of the two test bearings during the first life test. This saved extra schedule time and the potential bias to the test from switching between different test rigs for FL and CT operation.

In addition to the life test profile, a special on-orbit diagnostic test, referred to as the "4-Rev Test" (see Table I), was periodically performed. This was to evaluate the effectiveness of this on orbit trending technique used to forecast flight bearing degradation.

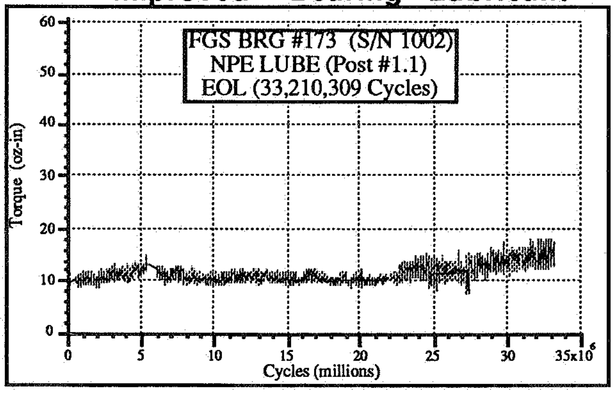
Results - The torque time histories of the test bearings (see Fig 10) showed that one of the flight test bearings showed significant signs of degradation after about 20 million CT cycles. This was similar to that observed in the first test and the observed on-orbit anomalies of FGS 2A. Somewhat surprisingly, the torque of the second "flight" bearing showed little change through 30 million cycles, beyond the mission equivalent of 2002. This paralleled the large scatter observed with the on orbit bearings in that the bearings in FGS 2A were clearly more degraded than the others in the remaining 5 Star Selector Servos (see CT bump flight data in Fig. 13). The bearing with the NPE oil showed relatively stable performance, despite the harshness associated with 30 million CT cycles.

Like FGS 2A, the torque of the degraded test bearing also approach the equivalent 10 volt torque saturation level (≈ 460 N-mm (65 oz-in)) after slewing past debris left from prior CT cycling as shown in Fig. 11. To generate such large torque bumps, it generally required more than 20 or 30 minutes of CT cycling. In this figure, the effect of subsequent ball roll overs in "flattening" the debris can be seen.

The 4-Rev diagnostic test followed the flight experience in that it was sensitive to DC level shifts in running torque and not transient torque bumps. As such it was used mainly for long term health monitoring of more permanent changes to bearing condition.



"Flight" Test Bearings



"Improved" Bearing Lubricant

Figure 10 - Running torque time histories of test bearings showing degradation of one Flight bearing at 20 M Cycles. Torque levels of the other test bearings were relatively stable despite the harshness of CT cycling.

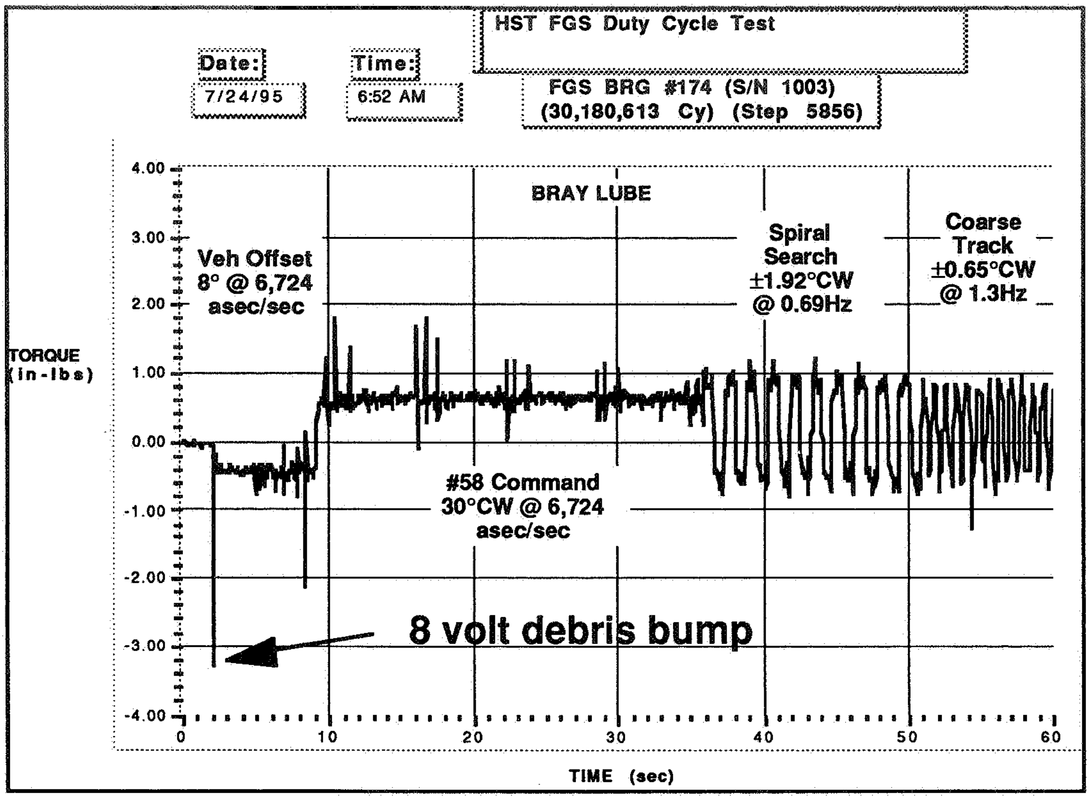


Figure 11 - Ground test bearing at 30 million Coarse Track cycles showing large torque bump due to piled up debris at end of CT stroke. Note the reduction in bump height in subsequent roll overs at ball spacing intervals.

<u>Comparison with Flight Data</u> - It is instructive to note that torque levels much higher than 10 volts was rarely observed, as if there was an equivalent yield strength to the lubricant debris. This is illustrated in Fig. 12 which shows a comparison between ground and on-orbit bearing peak torque bumps during Command #58 slews. Note that the torque of test bearing # 174 seems to limit out between 8 and 9 volts after 5 million CT cycles. Similarly, on-orbit bearing FGS 2A has gotten stuck and then freed around the 10 volt saturation level on numerous occasions in early '93, suggesting that it too reached some limit torque level.

Fig. 12 shows that peak equivalent torque from test bearing #171 seems to correlate well with that from a typical flight FGS bearing 1A. Although test bearing #174 appears to reach about the same torque saturation limit of flight FGS 2A, it does so at considerably fewer CT cycles.

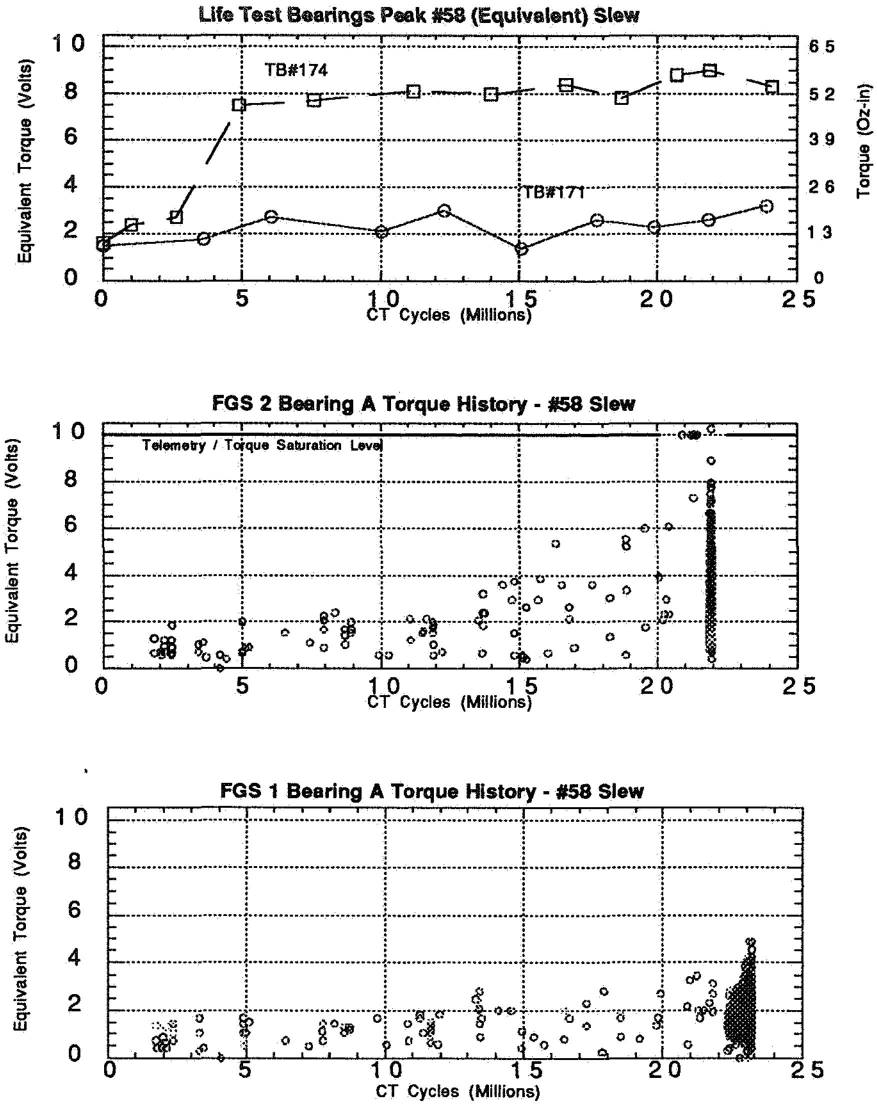
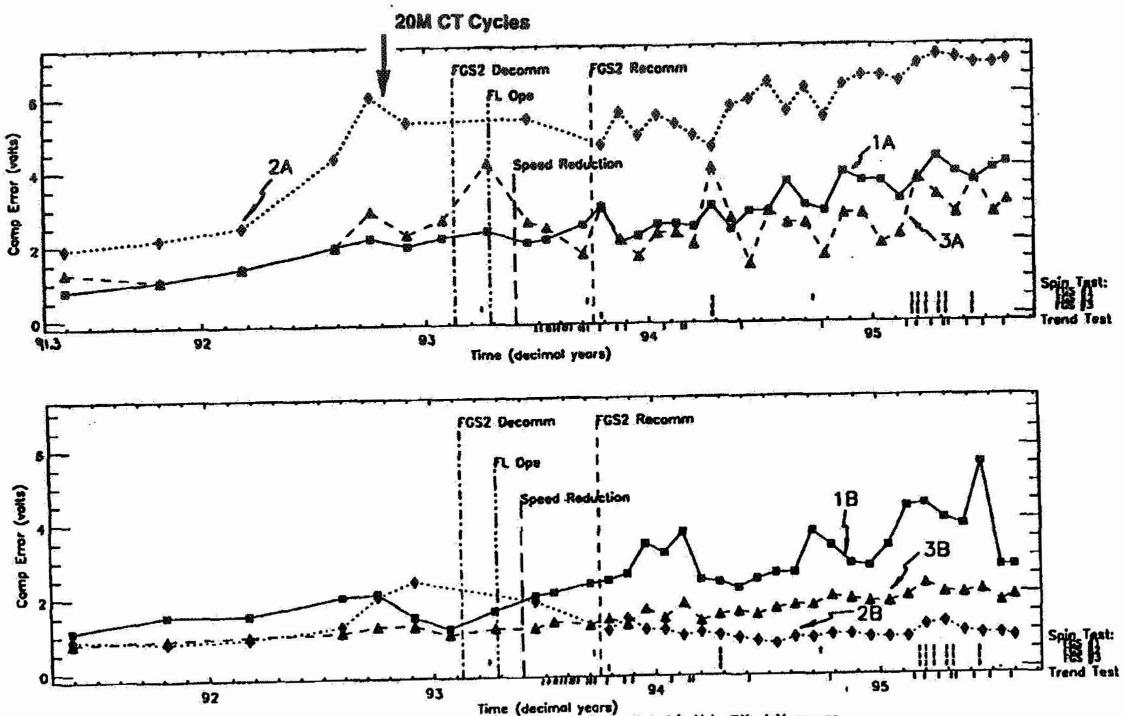


Figure 12 - Comparison of ground and flight bearing torque data. Test bearing #171 correlates with a typical FGS 1A but #174 reaches torque saturation sooner than FGS 2A.

The relative on-orbit health of the 6 sets of FGS bearings can be judged from Fig. 13. In this figure, the peak CT bump equivalent torque is recorded after a brief period (< 30 sec) of CT cycling during star acquisition. While the switch to primarily FL operation in early '93 help to stabilize FGS 2A's performance as well as that of 3A throughout '93, the torque started upward again about a year later. Also, the torque levels of the remaining FGS servos, although considerably lower than 2A, are also trending upward. Apparently, the lubricant chemical degradation process initiated by many millions of CT cycles is still continuing with time, even though the bearing duty cycle is considerably less damaging than before.



Bimonthly/Monthly Maximum Peak of CT Bumps Encountered in Veh. Offset Maneuver

Figure 13 Peak CT bumps of on-orbit bearings during acquisition showing upward torque trends despite minimizing CT cycling.

Teardown Inspection - Post-test teardown inspection showed surprisingly little damage to the test bearings. All bearings were still wet with free oil and, unlike the first test bearing set, showed a relatively small amount of lubricant debris most noticeable against the white background of the ball toroids (Fig. 14).

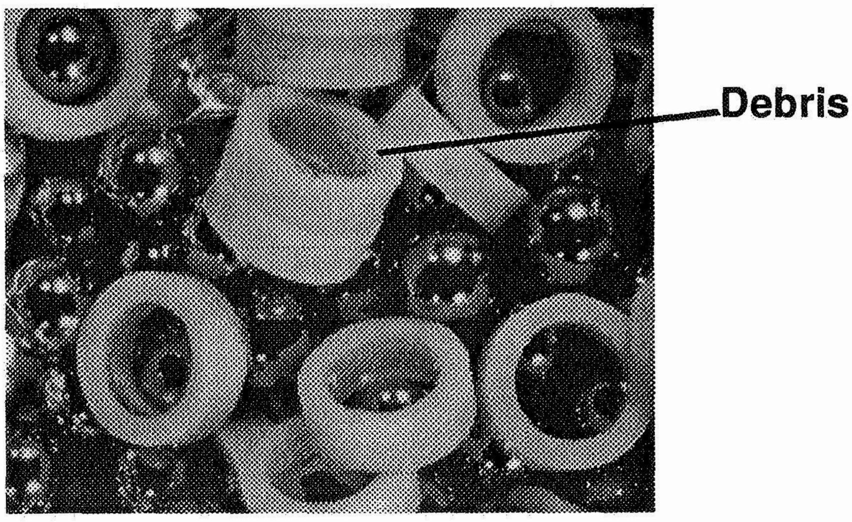


Figure 14 Test bearings were in remarkably good condition with free oil and small amounts of debris as shown here on the toroids of the worst test bearing #174.

Reversal Bump

Within the last year, an unusual type of torque anomaly was observed with one of the FGS servos causing disruption to HST science. Although not completely diagnosed at the time of this writing, a comprehensive evaluation of on-orbit data suggests that FGS bearings are the only likely cause of the anomaly which only occurs when the servo reverses direction. Typically, the bearing must reach a minimum slew rate of 300 arcseconds/sec in one direction before reversing direction. Also it must travel through at least 400 arcseconds in the opposite direction before the "reversal bump" is generated (Fig. 15). Another unusual characteristic of the reversal bump is that its peak torque is consistently located approximately 460 arcseconds from its point of turn around, no matter at which position the bearing changes direction. The equivalent driving torque of FGS 1 SSSB (solid line) is plotted in the upper panel of Fig. 15 and the associated slew rates are presented in the bottom panel. Note that a 6.1 volt reversal bump occurs after an initial 2.3 deg slew having a maximum rate of 430 arc-seconds/sec in the negative direction.

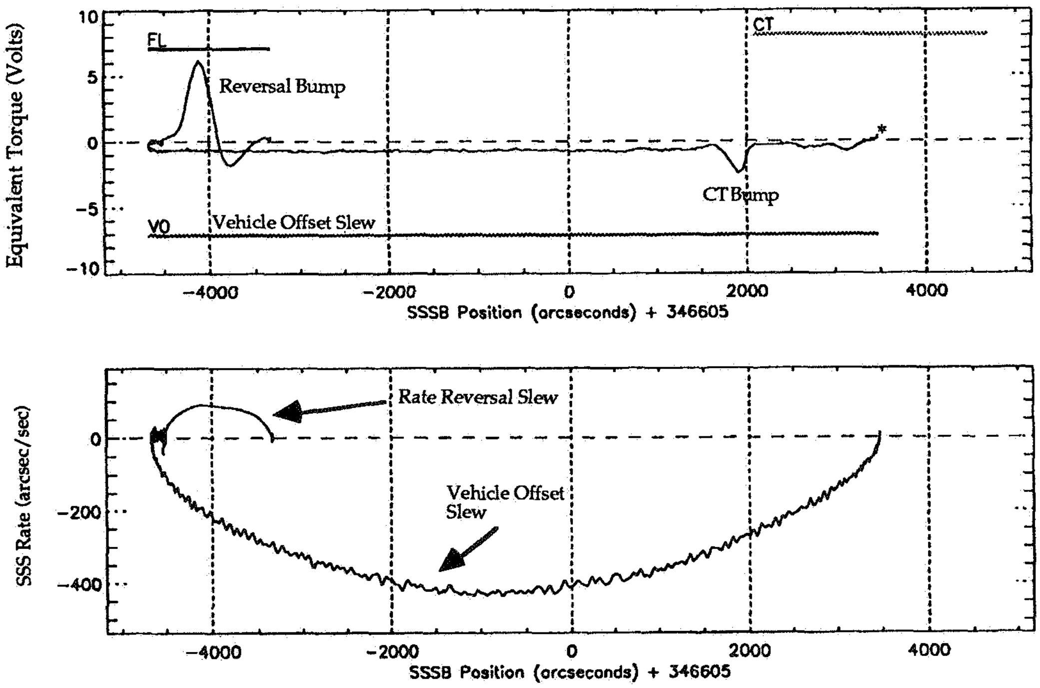


Figure 15 - Example of FGS 1 SSSB Reversal Bump. Initial direction of motion is right to left. Note CT bump at end of CT stroke (bar, upper panel). Direction reverses at a position of about -4,700 arcseconds and a 6.1 volt reversal bump forms.

Although two out of the 6 FGS SSS exhibit reversal bumps, only FGS 1 SSSB has reached torque levels that have caused acquisition failures. Currently, revisions to operating software are being implemented to minimize or eliminate this problem. The choice of which FGS to replace during the next servicing mission will depend on the effectiveness of this software workaround.

Concluding Remarks / Next Servicing Mission

The investigation has led to an appreciation of the need for a systematic approach to managing the operation of the pointing system of an observatory like HST. In particular, the value of systematic, on-orbit performance trending along with comprehensive, flight-like life testing of ball bearings on the ground has been validated. Correlation of flight and ground test data is not always achievable, but a comprehensive body of on-orbit and ground test observations can afford insight to beneficial operational workarounds and appropriate responses to operational anomalies.

Long duration, small angle CT gimbaling motion was found to hasten the degradation of the FGS bearings lubricant. Rolling over debris generated at the end of stroke caused torque levels to reach motor saturation levels. In contrast, significant improvements in torque performance were realized with a switch to FL operation. As verified by the ground test, this small motion within the ball/race elastic regime before the starting of rolling was found to be completely benign after hundreds of millions of cycles. This finding permitted unimpeded operation of HST without the burden of FGS 2 replacement during the first servicing mission.

Periodic, scheduled servicing of the HST affords a unique opportunity to implement the lessons learned from on-orbit and ground tests, and to remedy problems such as the observed FGS SSS ball bearing anomalies. Based on the current understanding of the compromised condition of the FGS ball bearings, replacement of an FGS is planned during the HST Second Servicing Mission, scheduled for February of 1997. If necessary, another replacement of an FGS can occur during the Third Servicing Mission, planned for December, 1999. Once a new FGS is installed in the HST, it will be operated in a manner which will avoid the type of SSS ball bearing degradation seen in the original units. Implementation of these learned lessons will help to assure that the HST continues to produce extraordinary astronomical discoveries well into the twenty-first century.

Acknowledgement

The authors would like to acknowledge the valuable contribution by Mr. George Damas to the FGS trending data presented in this study.