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THE ROLE OF BEARING AND SCAN MECHANISM LIFE TESTING IN FLIGHT QUALIFICATION OF THE MODIS INSTRUMENT

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ABSTRACT

This paper describes the results of accelerated and operational life tests on bearings for the Moderate Resolution Imaging Spectroradiometer (MODIS). It also describes the post test analysis of the disassembled bearings. Analysis was performed using micro-Raman, micro-FTIR, X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Microscopy (SEM), and Size Exclusion Chromatography (SEC). In general, the three sets of bearings in each of three test stations were in very good condition after accumulating 68, 144, and 209 million cycles, respectively. Some of the bearings exhibited lubricant degradation, indicated by viscous lubricant deposits on the cage and raceways.

INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument aboard the Terra (EOS AM-1) satellite and has been operating successfully since December 1999. The MODIS instrument's mission is to view the entire Earth's surface, gathering data to better understand the global dynamics and processes occurring on land, in the oceans, and in the lower atmosphere. All observations are made through an extremely high resolution, optically and mechanically precise, scan-mirror motor/encoder assembly. The reliable performance of this assembly depends on two duplex bearing pairs lubricated with Pennzane™ SHF-X-2000, a synthetic hydrocarbon, formulated with lead naphthenate.

As with most long-life lubricated mechanisms, lubricant life, bearing precision, and dynamic performance are the critical factors in the operation of the scan motor/encoder. As a first phase of lubricant selection for MODIS, bearings were tested with several candidate lubricants, accelerated life tests performed, and results evaluated. A synthetic hydrocarbon, Pennzane SHF-X-2000 with 2.5% lead naphthenate and 0.6% antioxidant additives, was selected. Phase one results have not been reported. The second phase of lubricant testing consisted of three bearing life tests. The results were reported in Ref. 1 and in this paper. The third phase was the successful qualification life test of the scan motor/encoder mechanism.

Each MODIS instrument contains a scan motor/encoder mechanism that has two duplex bearing pairs that are driven by a brushless dc-motor. To mitigate instrument risk, both accelerated and operational speed, lubricant life tests were conducted in parallel with the mechanism design and fabrication. This was done to verify the life early enough in the program to switch lubricants if accelerated testing revealed early anomalies.

At the onset of the MODIS development, Pennzane had not been flown on Goddard long life lubricated space mechanisms. Both accelerated and real-time life tests were conducted on MODIS scan bearings to demonstrate that Pennzane would successfully lubricate the mechanism for the 5-year (57 million cycle) life. Accelerated testing was achieved by increasing speed while increasing temperature to maintain a constant film thickness. Three stations were setup to test the bearings at various temperatures and speeds. A long-term test was also conducted on a full-scale motor/encoder, termed the life test unit (LTU). Short-term tests were also done using an engineering model (EM). Both units were flight quality.

Three more flight quality motor/encoder units were constructed. One was flown in the MODIS instrument on the TERRA satellite. Another will be flown in the MODIS instrument on the AQUA satellite later this year. The final mechanism remains as a spare.

Six months before launch of the Terra satellite (Dec 99), one of the accelerated life test stations was disassembled and two of the three bearing sets were found to be severely worn (Ref. 1). These results raised doubts about flightworthiness of the MODIS instrument. Fortunately, the LTU had been tested for almost five years at that time. Comparisons of torque margins and operating parameters between the EM scan mechanism, with only a few months of operating time, and the LTU mechanism showed no torque variation or operating parameter variation. From these measurements, it was concluded that no measurable bearing wear or lubricant degradation occurred during the long-term life test and that TERRA/MODIS instrument was safe to fly.

This paper describes the bearing wear and lubricant degradation and distribution after the accelerated bearing life tests and the real time life test (LTU).

EXPERIMENTAL

LIFE TEST STATIONS

Three test stations (II, III, IV) were setup for testing the bearings at various conditions. The test station is illustrated as Figure 1. Within each station, three flight quality, 440C steel, 66.675 mm (2.625 inch) outer diameter, 50.800 mm (2 inch) inner diameter, DF duplex pair bearings with a 165 N (37 pound) preload were mounted. The bearings, phenolic laminate retainers, and sintered nylon reservoirs were lubricated in accordance with flight requirements.

Each bearing pair was contained in its own clamp/housing. The housings also contained lubricant reservoirs. Station II and III housings were fitted with inner and outer race heaters. A strain gauge was mounted on a cantilever beam supporting each bearing enclosure to measure the torque. The inner races of three duplex pairs were driven by a common drive shaft. One telemetry platinum resistance thermometer (PRT) was mounted to each bearing outer race housing. Two control PRTs (Stations II and III only) were also mounted to each bearing housing (one for the outer race and one for the inner race). All testing was performed under vacuum.

Instantaneous torque readings were recorded every 15 minutes. The monthly average of these readings was plotted over the life of the test (see Figure 2).

Three sets of duplex MODIS bearings were tested in each station (for a total of nine duplex pairs) at the conditions listed in Table 1. Accelerated testing was achieved by increasing the shaft speed. The temperature was also increased to maintain a similar calculated specific film thickness (λ) in all three-test stations. This method was used as an arbitrary way of creating an accelerated lubrication life test.

Table 1 – Operational test station conditions

Station	Temp (°C)	Speed (RPM)	Total Cycles ($x10^6$)
II	45	72.0	209
III	37	50.0	144
IV	23	20.3	68

ENGINEERING MODULE (EM) AND LIFE TEST UNIT

Evaluation of the life test bearings from Station III had shown severe degradation (Ref. 1). To regain confidence in the MODIS scan mechanism before the launch of TERRA/MODIS, a performance evaluation was conducted on the like-new engineering model (EM) and the qualification life test mechanism after 4.7 years of testing.

The performance of the two test units was measured by evaluating the motor drag torque and phase error signals. The EM scanner had seen a few hundred thousand cycles whereas the LTU has completed more than one mission lifetime, approximately 58 million cycles, in vacuum testing.

Both scanners tested had their spin axis vertical with an equivalent inertia disk attached to represent the scanner mirror at the top end of the drive system shaft. The hardware used to record the drag torque and phase error signals was a portable data acquisition system running LabVIEW™ software and all data was recorded at 250 samples per second.

RESULTS

STATION II

Station II was an accelerated life test running at 72 RPM and 45°C. The original plan specified a life test duration of 57 million revolutions. After the bearing life tests successfully achieved the required 57 million revolutions, the test torque data was reviewed and it was concluded that there was no indication of failure so the tests were allowed to continue.

Average torque data is shown in Figure 3 for Station II. Intermittent jittering of the upper bearing pair housings was observed toward the end of testing. Torque characterization with and without visible vibration is shown in Figures 4 and 5.

STATION III

Bearing life test Station III (50 RPM and 37°C) results were reported at the 34th Aerospace Mechanisms Symposium (Ref. 1). Bearings in this station indicated consistent operation well past 57 million revolutions until a suspected heater malfunction occurred at 88 million cycles (Figure 2). The test continued until 144 million revolutions were achieved.

STATION IV

Station IV operated for 68 million cycles at 20.3 RPM, which is the speed for satellite operation. This station operated at room temperature (23°C) and exhibited vibration that randomly affected the bearings at different times. The vibration was visible and varied with intensity. At times there was no vibration noted on any of the bearings. Torque history for all bearing pairs appears in Figure 6.

STATION DISASSEMBLY

The decision to disassemble two of the test stations was finally made after station IV surpassed 57 million cycles. At the time of disassembly, station II had accumulated 209 million cycles while station IV had achieved 68 million cycles.

Upon disassembly some lubricant discoloration was observed, but none of the bearings had visible damage. The bottom bearings of each pair had more lubricant and a stickier feel than the upper bearings. Bearing torque remained well below the operational requirements of the system (18 oz-in drag torque) throughout the life test.

Photographs were taken throughout the disassembly and inspection process. A test station prior to disassembly is shown in Figure 7. The complete shaft and all bearing components were removed from the test station and transported to a class 100 flow bench in a class 100,000 clean room for further inspection.

One of the disassembled bearings (4-012) is shown in Figure 8. Although not easily seen in the macro photograph (Figure 8), dark viscous deposits were observed on the cage and raceways. A higher magnification photograph (Figure 9) shows an example of these deposits in a raceway. Two other photographs showing the variation and distribution of lubricant within the raceways appear in Figures 10 (greater amount of lubricant) and Figure 11 (lesser amount of lubricant).

Station II

Upon inspection, it was noted that some oil crept into the support cups. The oil was black and viscous and all balls, retainers and races were wetted, small meniscuses of oil were at the ball race junctions, and very limited wear was observed on the balls and races. Dark deposits of lead or lead naphthenate were not visible, indicating the lead naphthenate remained dissolved in Pennzane™. This formulation of Pennzane™ performed very well at high temperature and in the boundary lubrication regime.

Station III

When station III was disassembled, two of the three bearing sets were found to be severely worn. This is believed to be because of the heater malfunction (Ref. 1).

Station IV

As with station II, upon disassembling station IV it was noted that part of the oil had crept into the support structure. Again, the oil color was dark amber and the viscosity unchanged. All balls, retainers, and races were wetted and contained oil meniscuses. Almost no wear was observed on the balls or races.

The lubricant and bearing surfaces have been analyzed using micro-Raman, micro-FTIR, X-ray Photoelectron Spectroscopy (XPS), Scanning Electron Microscopy (SEM) and Size Exclusion Chromatography (SEC) and the results summarized later in this paper.

Comparison of the bearing wear and the lubricant degradation after life testing at 23°C and 45°C, clearly demonstrated that the severe bearing damage found in the 37°C accelerated life test originated from a thermal control failure that drove the bearing test temperature well above 90°C, as suggested in Reference 1.

EM AND LTU

The steady state drag torques measured on the MODIS EM and LTU scanner units were approximately 9.4 and 12.2 oz.-in. respectively, indicating a beginning-of-life and a end-of-life torque margin of greater than 20. The more important parameter of margin on phase lock for both units is a healthy 200 percent. Because of the design similarities between the EM and LTU scanner units and the MODIS scanners that are in flight or scheduled for flight, it was concluded that the flight unit MODIS scanners have sufficient margin for a five-year mission life on the Terra and EOS-PM programs. A more detailed description of the comparison appears later in this paper.

ANALYTICAL RESULTS

In general, the results showed the balls, retainers, and races were still lubricated and in good condition at the end of test. The top bearing assemblies had the least lubricant of the three bearing pairs in both stations II and IV and bottom bearing assemblies had a thicker grease-type residue. There was no sign of dry debris in any of the bearing assemblies. The oil had darkened significantly and was more viscous, almost like honey. Wear paths were seen in the races and on some of the balls. There was no sign of elongation in the retainer pockets. However, some slight metallic debris was observed on some of the retainers. The metallic debris was noticed only on station IV.

Raman and Infrared analyses of the lubricant indicated the standard signature for non-degraded Pennzane™. XPS, SEM, and EDAX showed the normal elemental composition for 440C steel. The most striking demonstration of lubricant degradation was observed in some bearings as a thickened lubricant deposit with a grease-like consistency. These deposits occurred on both races and on the cage. For the Size Exclusion Chromatography (SEC) analysis, the cages were all weighed and then extracted using tetrahydrofuran (THF). The solution was concentrated and injected into a size exclusion chromatograph. An example from bearing 4-012 appears in Figure 12. Detector signal is plotted as a function of molecular weight (MW). Several peaks are evident. The negative peaks at low MW are injection peaks. The peak at 195, which occurs in all samples, is an artifact from a preservative in the mobile phase (THF). The next peak represents the disubstituted Pennzane™ compound. The higher MW peak, at about 1,300, represents the primary Pennzane™ material as well as a contribution from the lead naphthenate. The broad high MW peak, centered about 18,000, represents polymerized lubricant. This high MW peak does not occur in unused samples.

The weight of extracted lubricant from the cages varied from bearing to bearing with the smallest amount being about 9 mg from cage 4-015 to 49 mg from cage 4-002A. This compares to the nominal amount of 75 mg impregnated at build up. In addition, dark residues were observed on cages 4-002A, 4-005A, 4-006A and 4-015A. Photographs for these two cages after THF extraction appear in Figures 13a and 13b.

PERFORMANCE MEASUREMENT TEST

Performance tests on the MODIS engineering model (EM) and life test unit (LTU) scanners were made to determine the changes in performance over the expected on-orbit life of the flight unit. Scan motor drag torque and phase error signal performance from both test units was measured, recorded and evaluated. The EM scanner had seen a few hundred thousand rotation cycles whereas the LTU had completed more than one mission lifetime and about 58 million cycles in vacuum testing.

Figure 14 documents the running or steady state drag torque of the EM scanner, which had an average value of .067 N-m (9.4 oz-in). During this test, the EM unit maintained the required rotation rate of 20.3 rpm with phase-lock control. The beginning-of-life requirement for this value was 0.11 N-m (15 oz-in), which was met. This represents a beginning of life torque margin greater than 20.

Figure 15 documents the measured phase error signal of the EM scanner under turn ON and steady state conditions. When the scanner was initially turned on, there was a large error signal generated between the commanded rate and the actual rate, shown by the indicated spike shortly after turn-on. The phase-lock circuitry was designed to reduce the error between the commanded rate and the actual rate over a given time, therefore the error signal reduced shortly after turn-on to a value of approximately 1 volt peak-to-peak. This was equivalent to a phase error of approximately 20 micro-radians under steady state scanner rotation.

Figures 16 and 17 show an attempt to bring the EM scanner out of phase lock by increasing the external drag torque on the drive system. Due to the limitation of the test setup, the external drag was increased manually while monitoring the system till the scanner was out of phase lock. The two figures also show maximum drag torque when the scanner went out of phase lock. The drag torque was compared to the maximum available torque of the scanner motor and the torque margin established. When the transient drag torque events on Figures 16 and 17 were omitted and the maximum drag from the eight attempts averaging, the drag torque when the scanner phase lock was lost occurred at about 0.71 N-m (100 oz-in). This represents a margin on phase lock of about 200% at the beginning-of-life.

Figure 18 documents the steady-state drag torque of the LTU scanner. After completing more than 58 million cycles in vacuum, the LTU has an average value of 0.086 N-m (12.2 oz-in).

The measurement indicated that at the end of one mission life, the torque margin for the scanner was greater than 20.

Figure 19 documents the measured phase error signal of the LTU scanner under turn ON and steady state conditions. Similarly as with the EM unit system, when the LTU scanner was initially turned on, there was a large error signal generated between the commanded rate and the actual rate, shown by the indicated spike shortly after turn-on. The phase-lock circuitry was designed to reduce the error between the commanded rate and the actual rate over a given time; therefore there was a reduction in error signal shortly after turn-on to a value of about 0.5 volt peak-to-peak. This was equivalent to a phase error of about 10 micro-radians under LTU scanner steady-state rotation.

Due to the LTU scanner test vacuum apparatus, it was not possible to perform the phase lock tests for comparison to the EM data. Nonetheless, based on phase error and drag torque measurements there was good confidence that the life test unit, after greater than one mission life, had no significant difference in measurable parameters and therefore has good correlation in margin for phase lock equivalent to the EM unit measured data.

CONCLUSIONS

The steady state drag torques measured on the MODIS EM and LTU scanner units were approximately 0.067 N-m (9.4 oz-in) and 0.087 N-m (12.2 oz-in) respectively, indicating a beginning-of-life and a end-of-life torque margin of greater than 20. Phase lock margin, the more important parameter, for both units was a healthy 200 percent. Because of the design similarities between the EM and LTU scanner units and the flight scanners, it was concluded that the flight scanners had sufficient margin for the five-year mission.

LESSONS LEARNED

Since a worn slip ring was the cause of heater loss in the accelerated test station, it was shown that the test equipment must be more robust than the hardware being tested. Also, in the presence of gravity, considerations for the orientation of test samples should be given. Where feasible, rotation of the samples should be performed to counter the effects of gravity. The labyrinth seal should match that of the flight configuration. And lastly, when testing mechanical systems, consider the frequency of the test apparatus. In this test it was noted that jitter, seen during life testing, was likely due to the cantilevered test arm resonating or coupling with the rotational speed of the bearings.

REFERENCES

1. Brian J. Dietz, Steven G. VanDyk and Roamer E. Predmore, "Earth Scanner Bearing Accelerated Life Test", 34th Aerospace Mechanisms Symposium, May 2000, pp. 303–316.

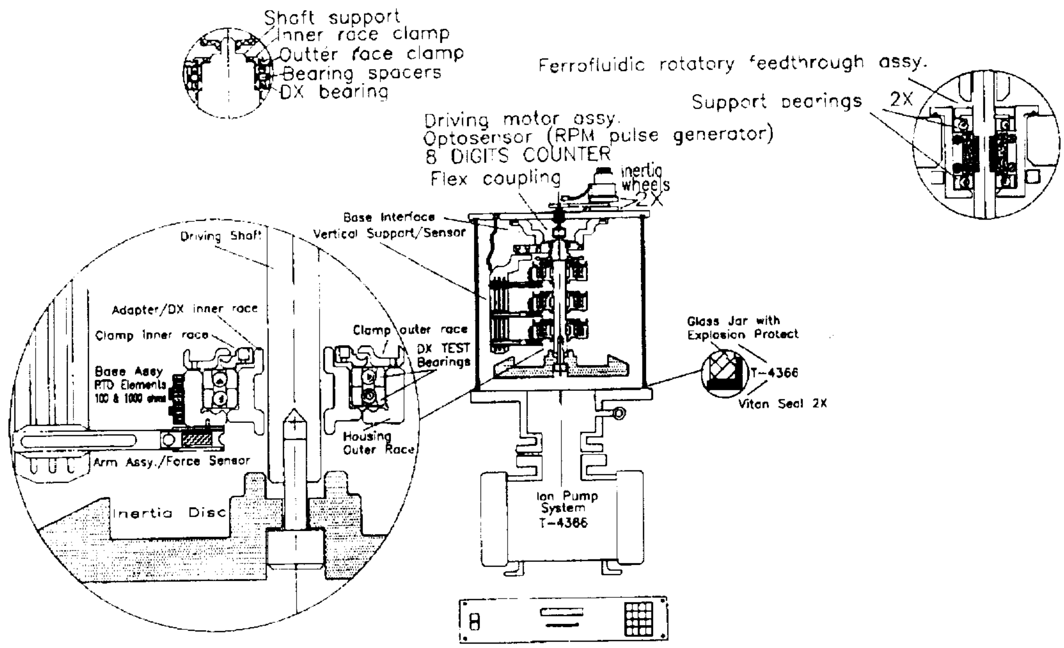


Figure 1 – Test Station

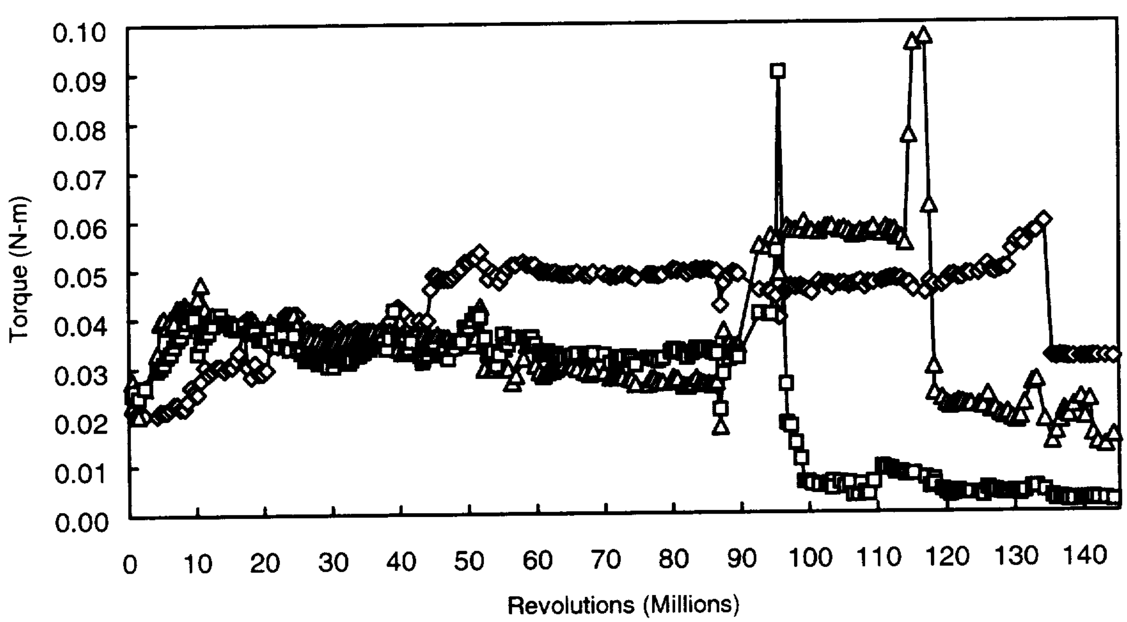


Figure 2 – Torque vs. revolutions for upper pair bearings (III1), middle bearings (III2), and lower bearings (III3)

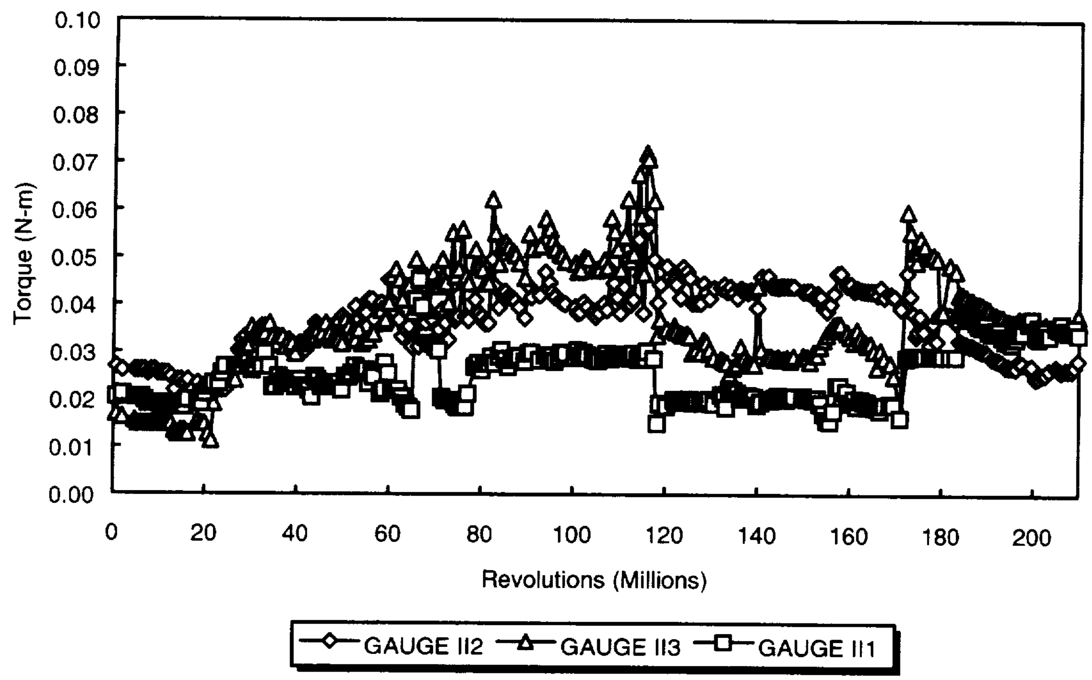


Figure 3 – Torque vs. revolutions for upper pair bearings (II1), middle bearings (II2), and lower bearings (II3)

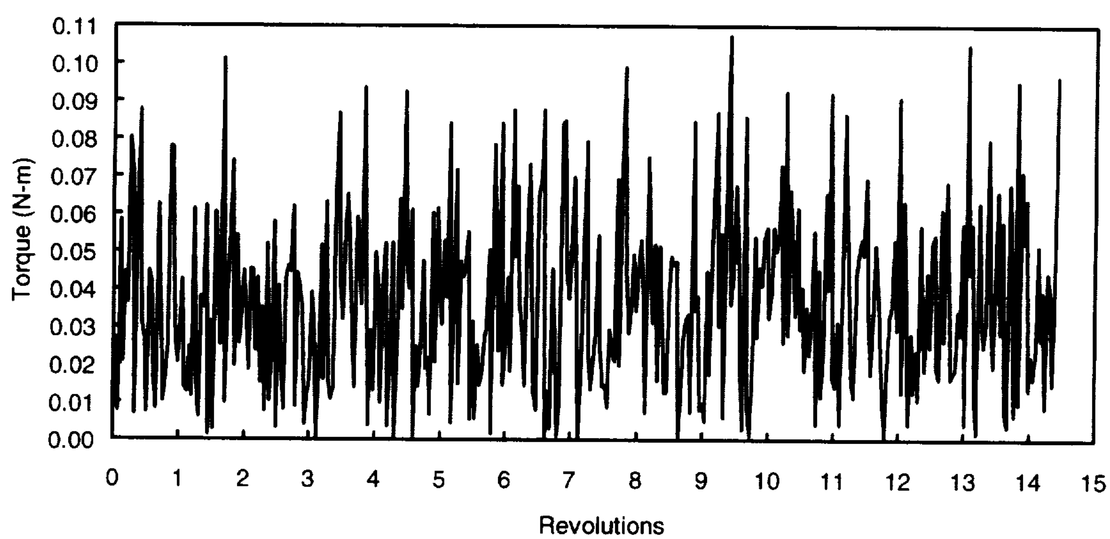


Figure 4 – Torque characterization for Station II upper bearing pair with visible vibration

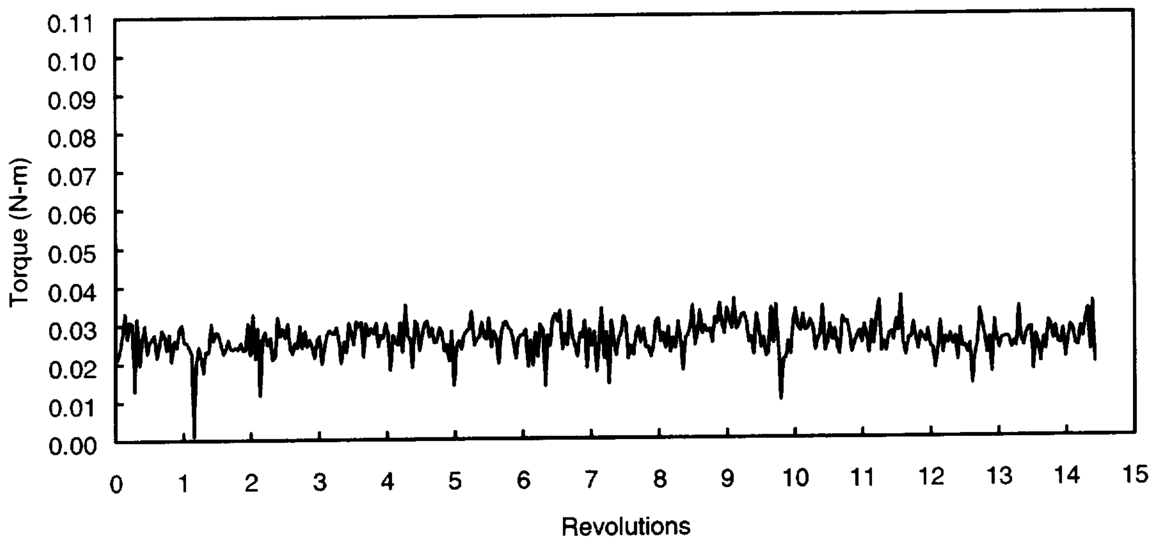


Figure 5 – Torque Characterization for Station II Middle Bearings without Vibration

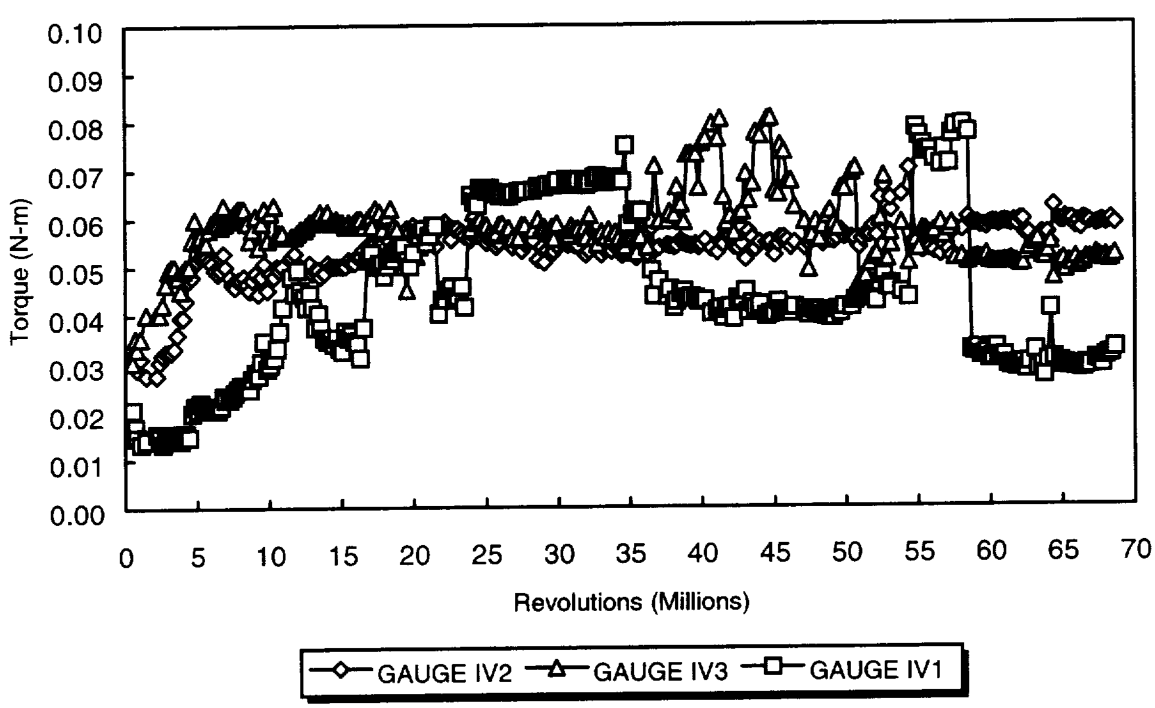


Figure 6 – Torque vs. revolutions for station IV upper pair bearings (IV1), middle bearings (IV2), and lower bearings (IV3)

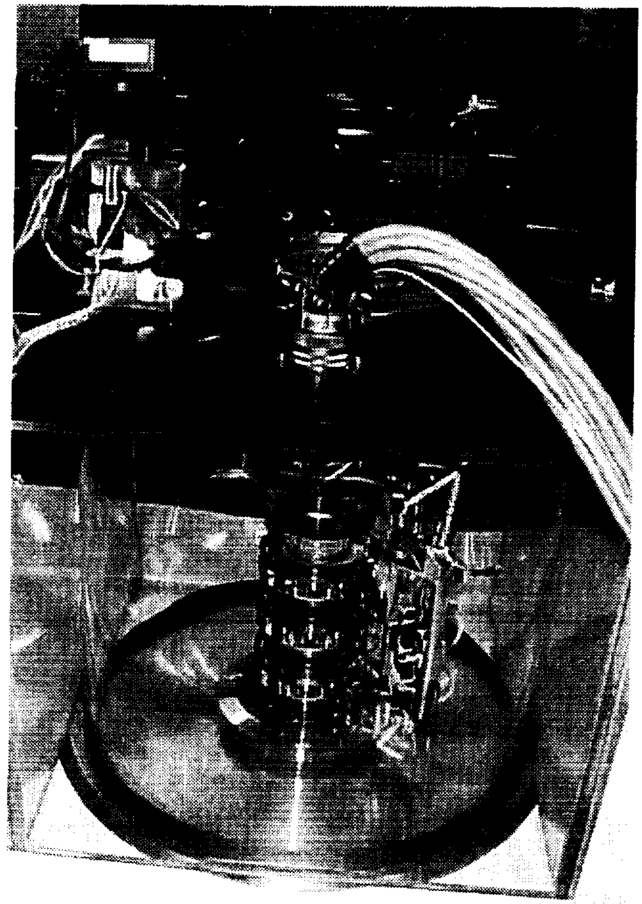


Figure 7 – Test station prior to disassembly

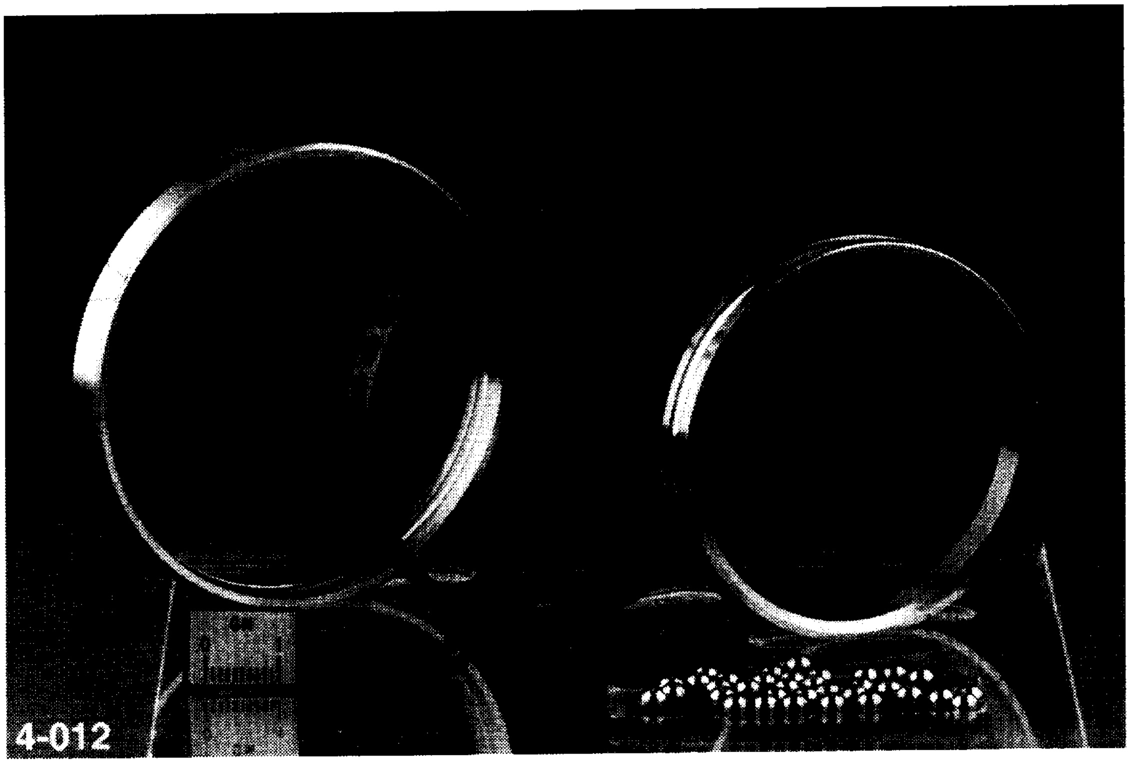


Figure 8 – Disassembled MODIS 4-012 bearing

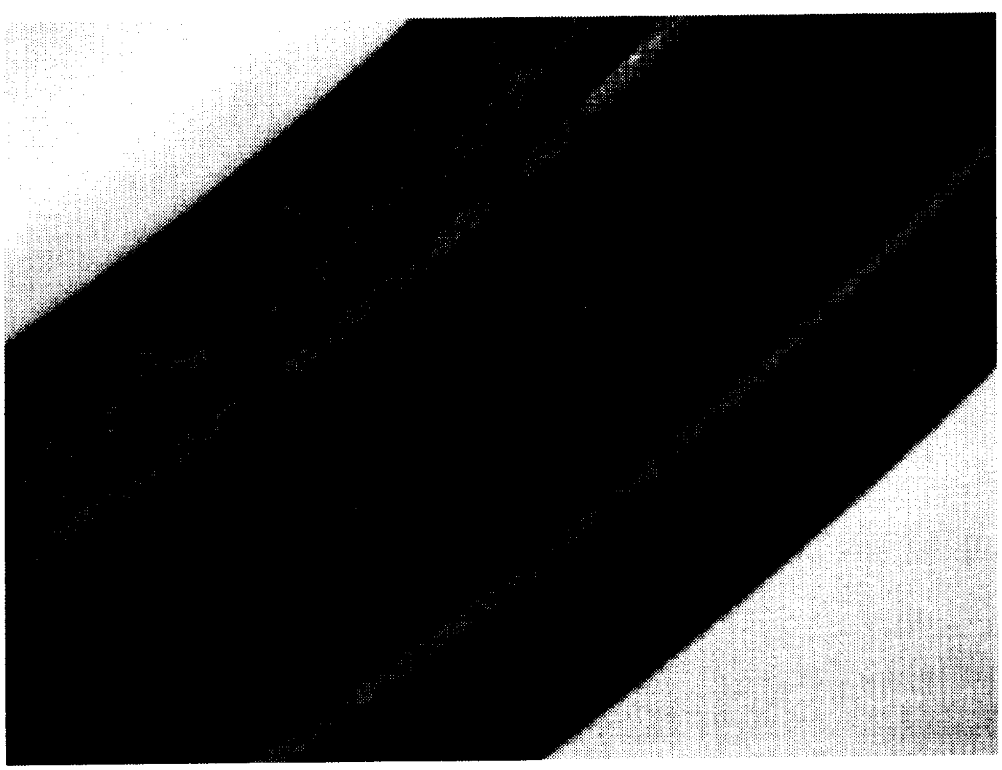


Figure 9 – Darkened lubricant deposit

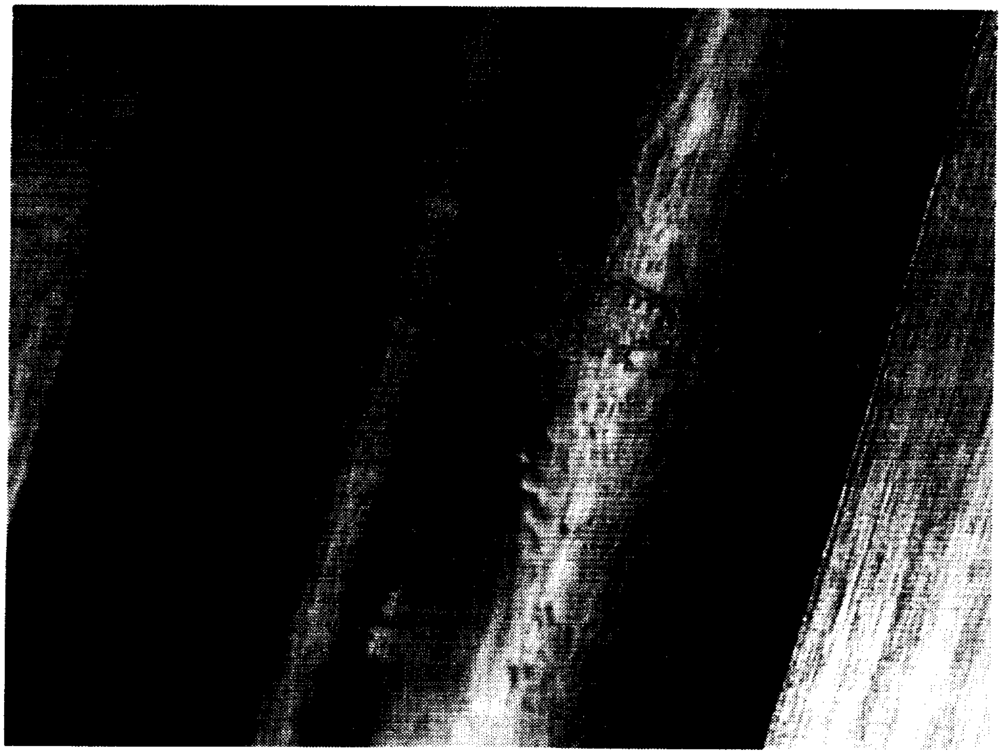


Figure 10 – One bearing from station II with a greater amount of lubricant

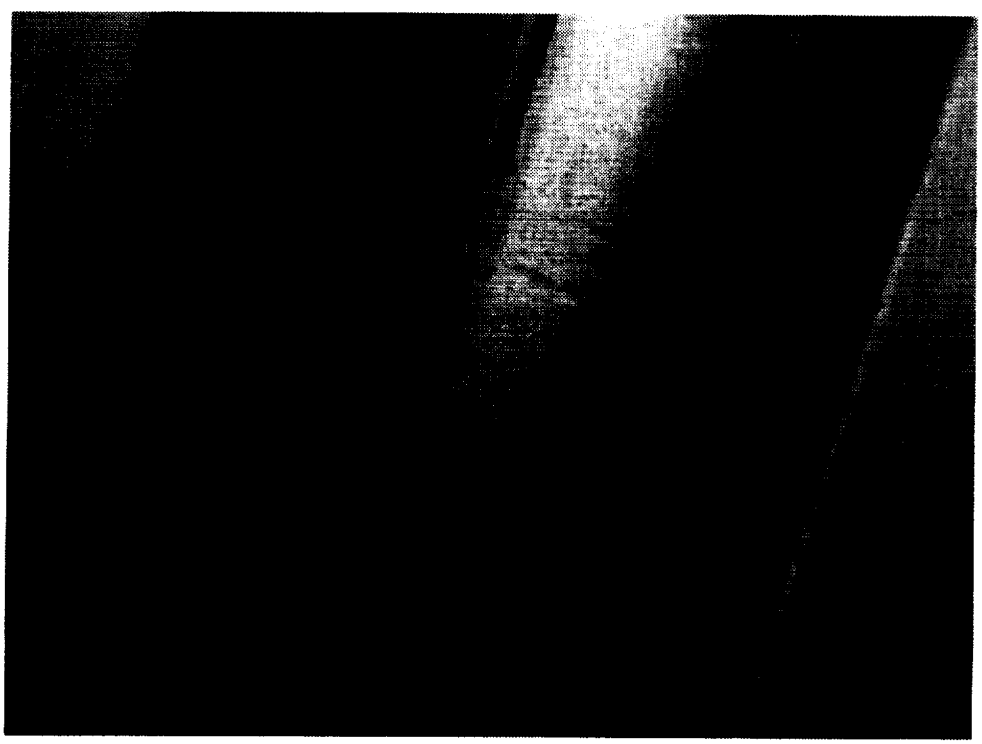


Figure 11 – One bearing from station II with a lesser amount of lubricant

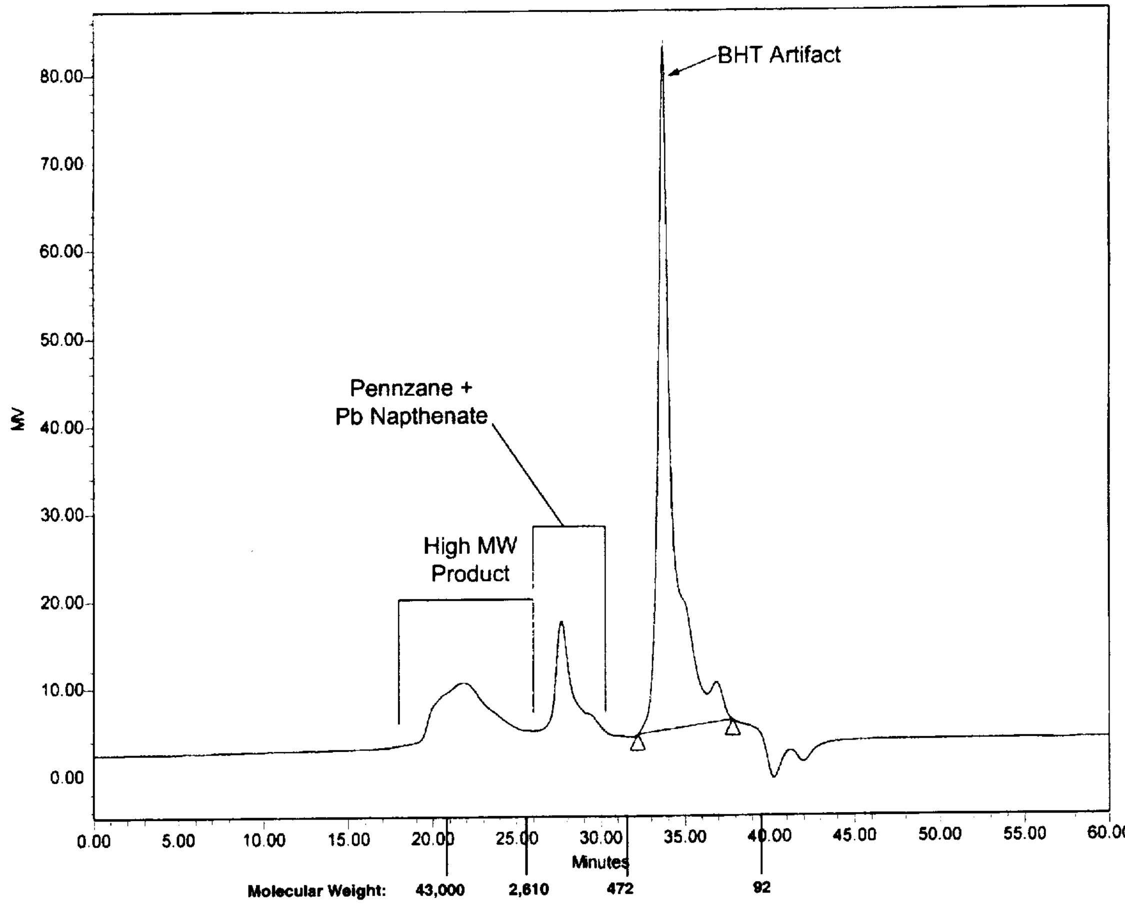
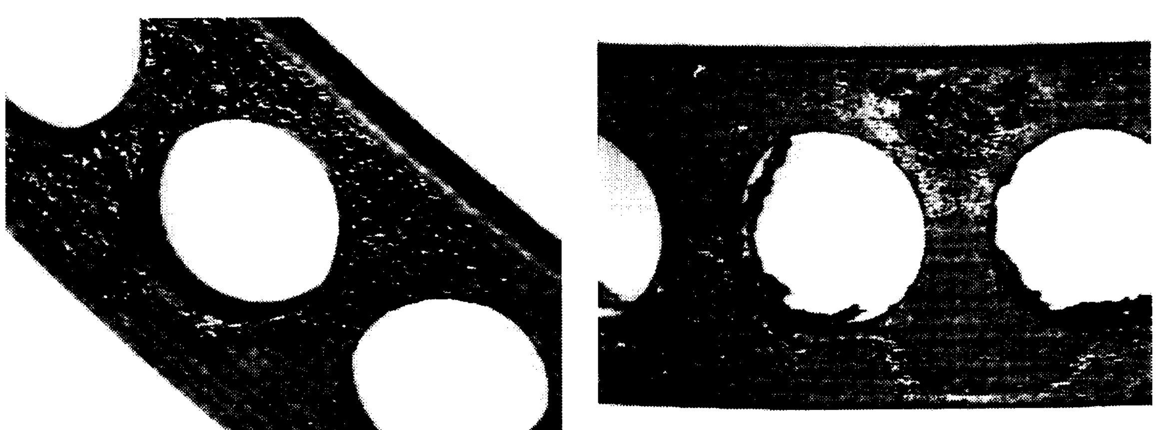


Figure 12 – Size exclusion chromatogram from extracted lubricant from cage 4-012



(a) (b)

Figure 13 – Photograph of extracted cage from 4-002A (a) and 4-015A (b)

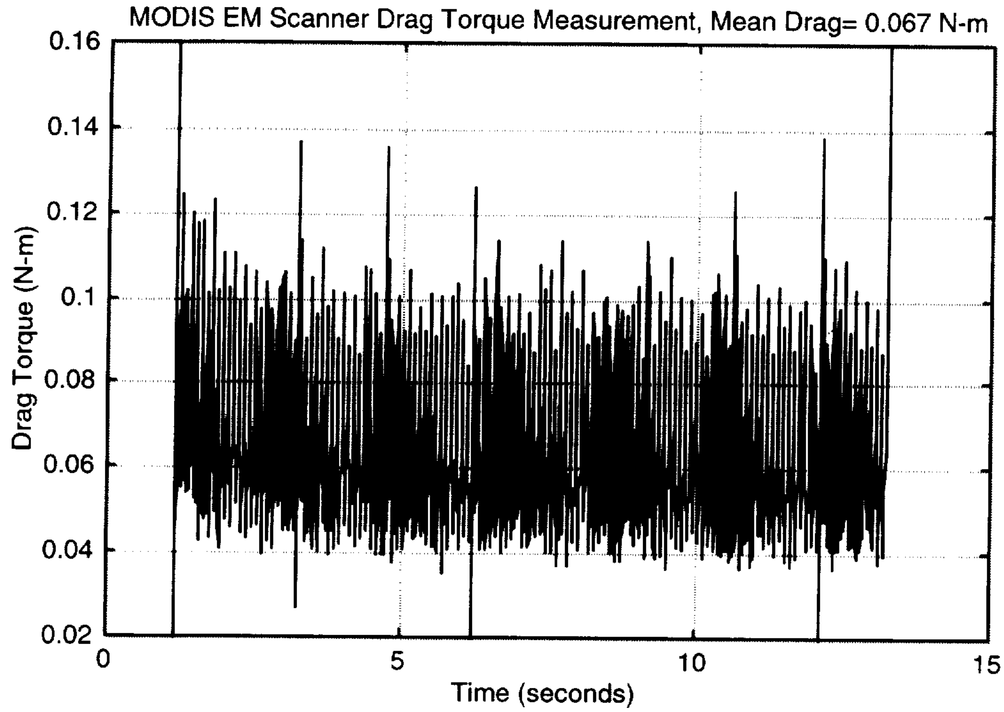


Figure 14 – MODIS EM Scanner Steady State Drag Torque

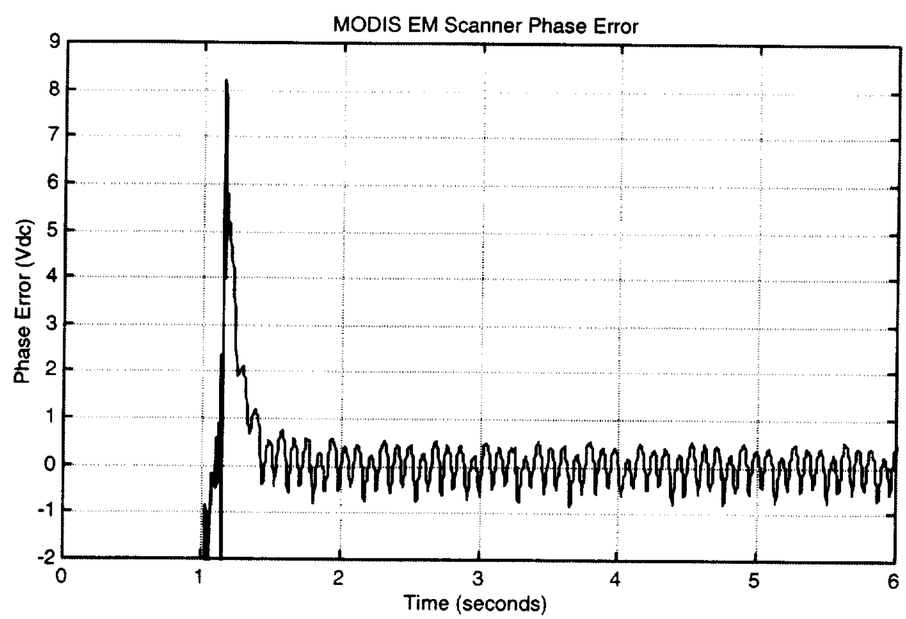


Figure 15 – MODIS EM Scanner Phase Error

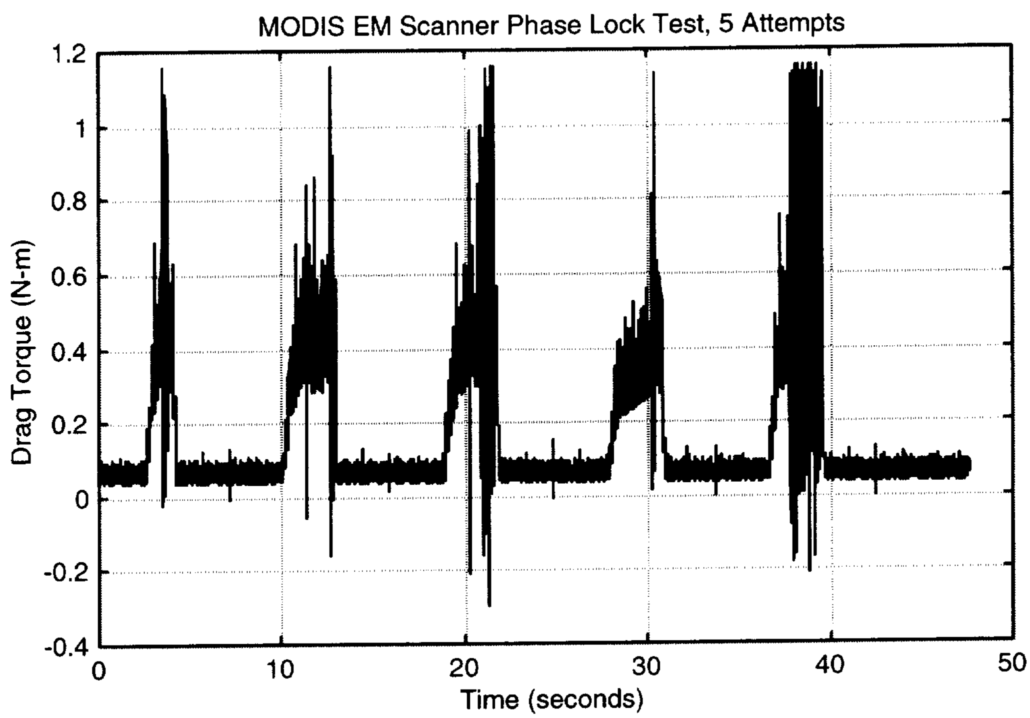


Figure 16 – MODIS EM Scanner Phase Lock Test 1

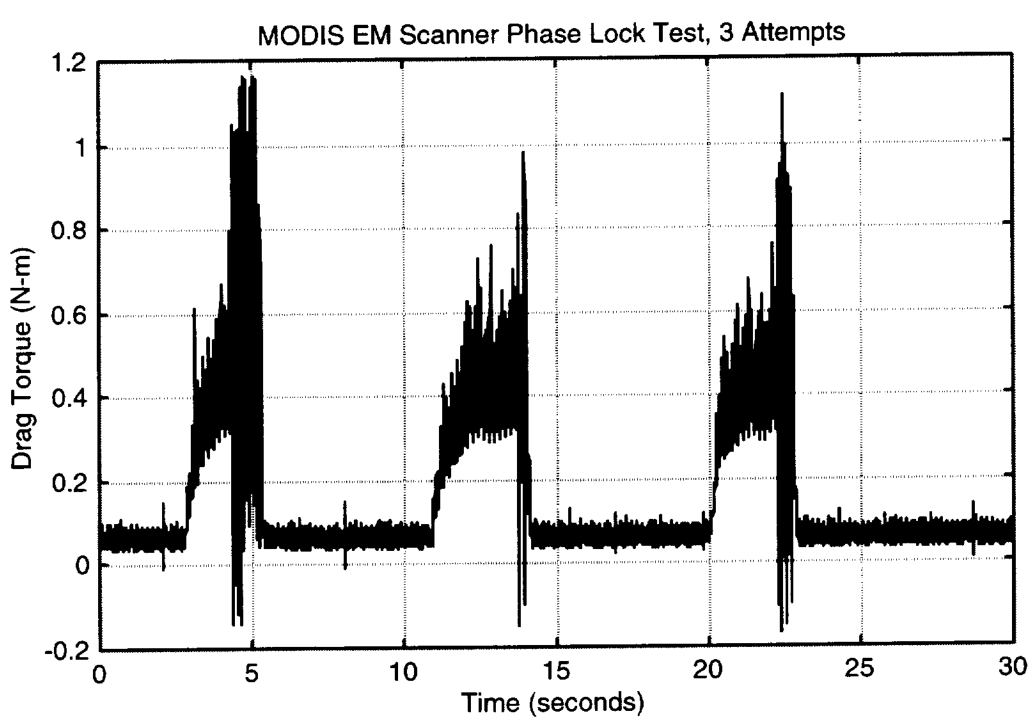


Figure 17 – MODIS EM Scanner Phase Lock Test 2

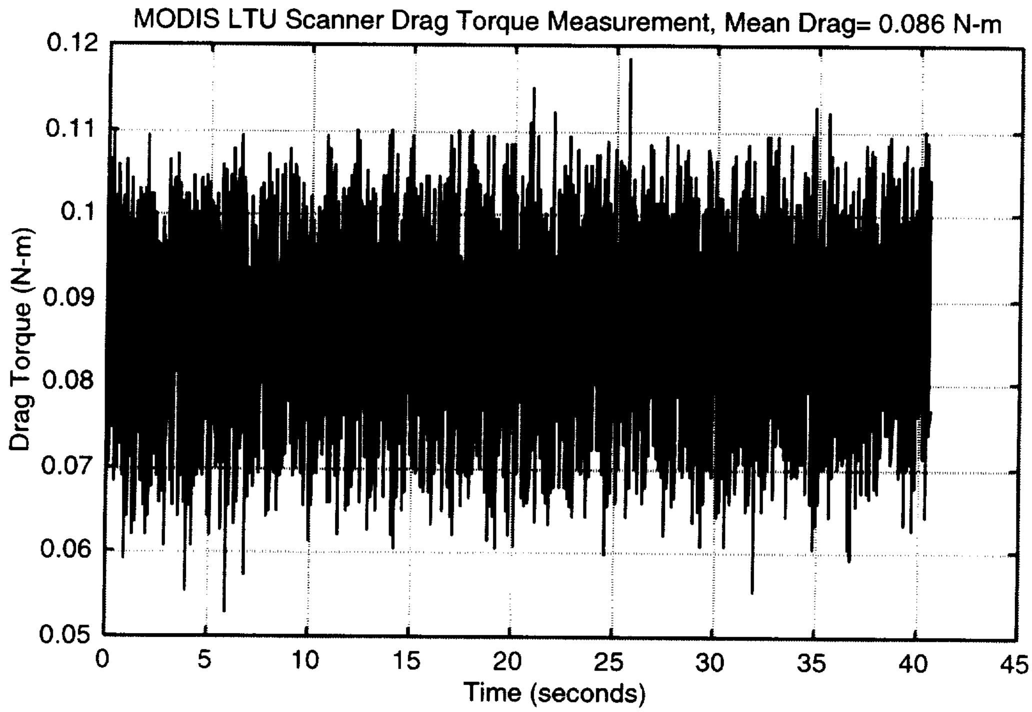


Figure 18 – MODIS LTU Scanner Steady State Drag Torque

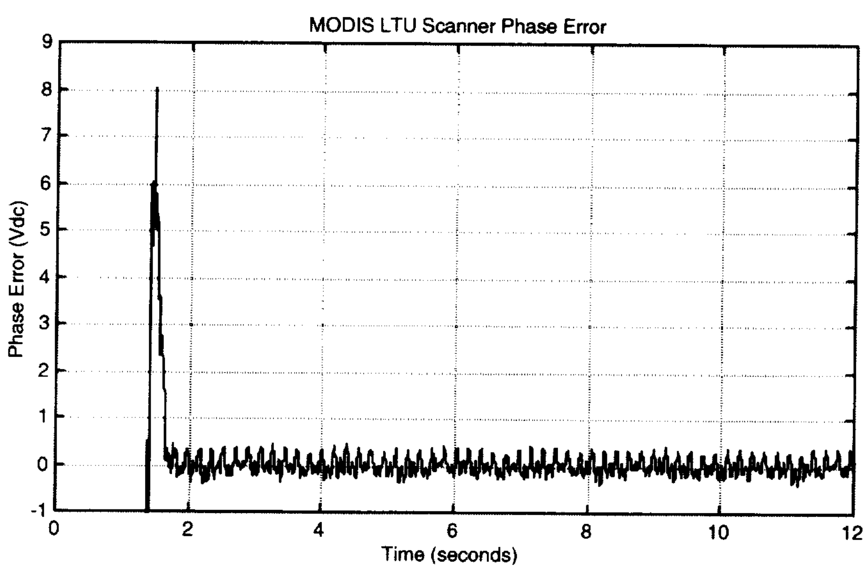


Figure 19 – MODIS LTU Scanner Phase Error

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13. ABSTRACT ***(Maximum 200 words)***

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