Suomi-NPP Mission On-orbit Experience with Toroid Ball Bearing Retainers under Unidirectional and Reversing Motion

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Abstract

The Advanced Technology Microwave Sounder (ATMS) instrument scan system on the Suomi National Polar-orbiting Partnership (SNPP) spacecraft has experienced several randomly occurring increased torque ‘events’ since its on-orbit activation in November 2011. Based on a review of on-orbit telemetry data and data gathered from scan mechanism bearing life testing on the ground, the conclusion was drawn that some degradation of Teflon toroid ball retainers was occurring in the instrument Scan Drive Mechanism. A life extension program was developed and executed on-orbit with very good results to date. The life extension program consisted of reversing the mechanism for a limited number of consecutive scans every day.

Introduction

The ATMS scan mechanism has been described in references 1 and 2, so only a cursory description is included. This paper is devoted to root identification of the ATMS scan bearing torque events, evaluation of sensor impacts, and mechanism life evaluation by resolving the differences between the ATMS bearing experience vs other more positive on-orbit experience. In addition, part of the paper discusses the implementation of an on-orbit life extension mitigation on the SNPP spacecraft.

Figure 1 depicts the scan mechanism in cross section, which identifies the major components of the assembly. Note that there are two sets of bearings in this assembly. The problem is only observable with the Main Motor bearings for ATMS. The Compensator Motor bearings are identical to the Main Motor bearings, but run at a rate of 1.8X the Main Motor rotation rate and have not shown any misbehavior. At this time, we don’t know why the Compensator Motor bearings are acting differently than the Main Motor bearings.

Figure 2 depicts the bearings in question, showing the arrangement of the balls and the retainers. The bearings are an angular contact pair manufactured by Timken. The bearing pairs have an OD of 57.15 mm (2.0 inches), with each bearing having a complement of 38 3.175-mm (0.125-inch) balls and 19 toroids. The nominal contact angle is 20 deg. Bearing preload is 44.5 newtons (10 pounds).

The bearings are lubricated with Nye Rheolube 2000B. The design life of the ATMS instrument is 7 years.

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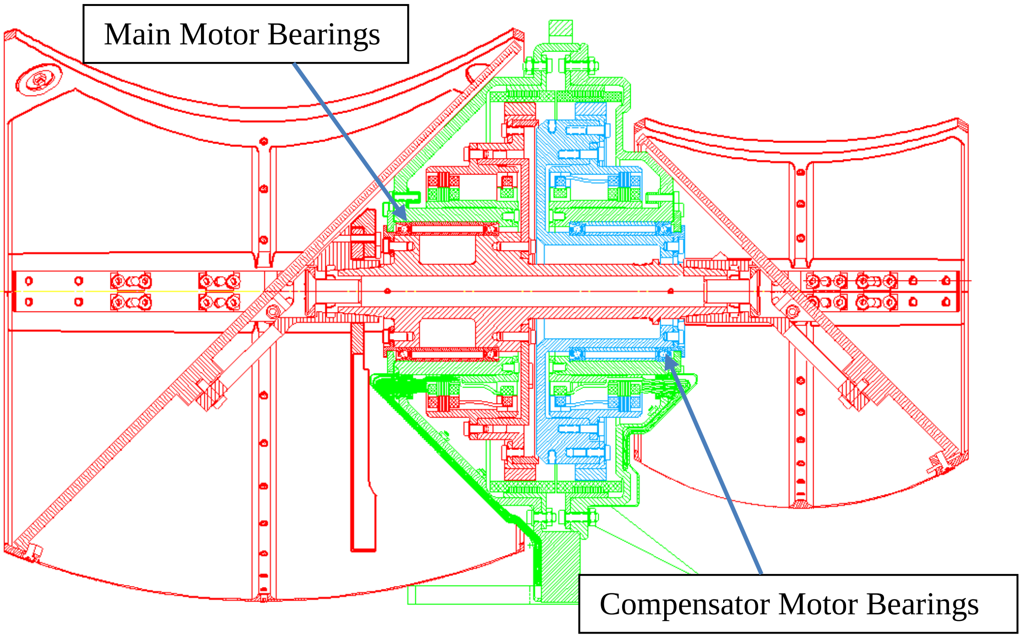


Figure 1. ATMS Scanner Cross-Section

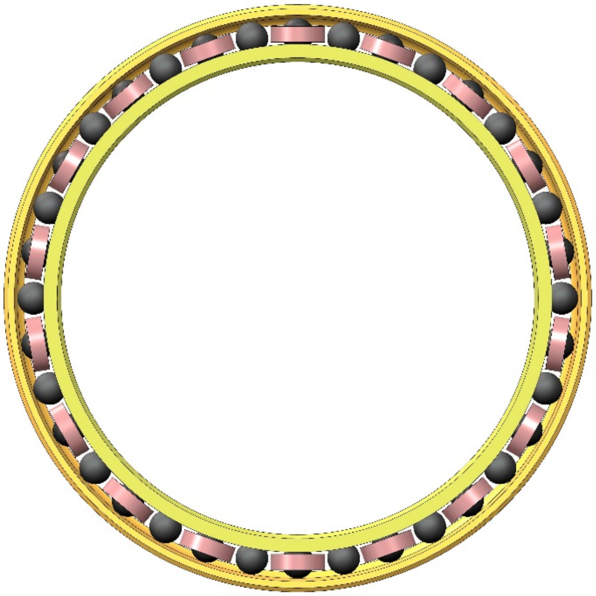


Figure 2. Nominal ATMS Bearing Configuration

On-orbit Indications of a Problem

The SNPP spacecraft was launched on October 28, 2011. The ATMS instrument started operations on Nov 8, 2011 and has since been in continual operations. The instrument experienced its first indications of scanner related problems about a year later. The indications of problems were based on evaluation of main motor current spikes and related motor control telemetry.

Efforts were made to find common ground between the experiences from the bearing life test unit results and the on-orbit flight unit data. This effort was complicated by the fact that the life test units were focused on only the mechanism bearing assemblies and that the on-orbit data were being obtained from a higher level of mechanism assembly. The telemetry obtained for the life test units were not directly relatable to the telemetry available from on-orbit. As an example, the temperature telemetry in the test units was a better indicator of average bearing temperature, while the on-orbit implementation was more of a drive motor temperature. This type of data divergence made the evaluation of the on-orbit motor current spikes much more difficult. We found that the best common data relationship was that of average motor current. We had higher rate motor current data for both the test unit and the on-orbit instrument. However, the data rates were vastly different and the motors were driven by very different control systems. That made any useful comparison of the high rate data from both sources almost impossible. Still, the high rate on-orbit data did provide valuable information on what was going on within the flight mechanism bearing system.

Figure 3 provides some information on the initial on-orbit observation. This shows the main torque trend from the beginning of mission to end of February, 2014. The transient in late 2012 returns to the previous nominal condition on its own with no intervention from the ground or otherwise.

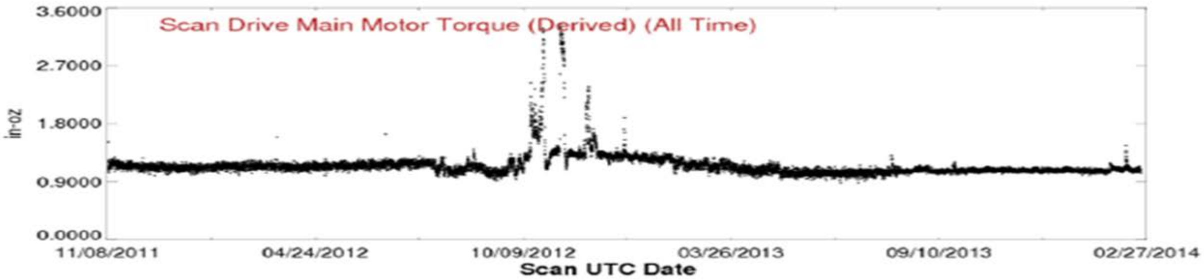


Figure 3. On-Orbit Main Motor Current – showing the torque spike in late 2012

ATMS Life Test Unit Experience

The ATMS program initiated a bearing life test program on February 2003 with the first of three bearing test units. This was for the same toroid type separator bearings. All three units went on line by August 2003.

Test unit 2 started experiencing higher torque spikes at about the 5 year mark of its ‘operational’ life. The torque generated by the unit exceeded limits at the 5.3 year mark of its life (2/20/2009). At this point, the unit was disassembled to inspect the bearings. It was found that the bearing toroids had experienced severe wear. The toroids of one end of the bearing pair were almost totally destroyed and the other bearing showed severe wear of the toroids. The temperature of the test units was initially set at 41 °C as a predicted worst case temperature. In the September 2012 timeframe the temperature was changed to more closely match that of the measured on-orbit values. The test unit temperature was changed from 41 °C to 18 °C. At the time, it was thought that the accelerated wear of the test unit #2 bearings was the result of an overly conservative temperature prediction leading to a premature loss of lubrication.

The higher test temperature did contribute to a very conservative test. The protective elasto-hydrodynamic film thickness between the bearing balls and race differed by a factor of 2X. Also the chemical degradation rate of the lubricant was accelerated by temperature approximately doubling for every 10°C according to the Arrhenius relationship. However the sister unit #1 and #3 test bearings ran approximately twice as long as the #2 bearings so there was yet another unidentified factor present.

Figure 4 shows the wear of the bearing toroids for test unit 2. The left picture shows the ‘heater’ end bearing and the left shows the ‘encoder’ end bearing. The ‘heater’ end bearing was thought to run at a slightly higher temperature than the other, leading to more severe wear.

Figure 4. Test Unit #2 bearing condition from 2009 disassembly

The other units (1 and 3) continued to run beyond their 7-year design lives, but test unit #3 exceeded its torque limits on 6/29/2012 and was taken off line. At this point in time, it was decided to switch out the drive motor of the unit to more closely match the torque capability of the flight motor. The original test set motors had a torque capability of 69 in-oz (0.49 N-m) continuous duty, with a 120 in-oz (0.85 N-m) peak capability. While the flight motor had a torque capability of 120 in-oz (0.85 N-m) continuous duty with a 300 in-oz (2.1 N-m) peak capability. The replacement motor chosen for test station 3 closely matched the capability of flight motor. This switch of the motors was completed in March, 2014 and the unit was restarted.

Recent Developments

In late 2014, the SNPP ATMS instrument started to experience some more elevated motor current spikes. This lead to the re-institution of the Scanner Drive Working Group. The working group was tasked with the evaluation of the on-orbit situation and to provide recommendations for mechanism life extension mitigations.

This lead to a variety of work, starting with a re-evaluation of the work on bearing life prediction, applicability of life test data on other programs, work done in 2009 on the test unit 2 etc.

A re-evaluation of related life test data by Stu Loewenthal of Lockheed Martin suggested that the differences in life test results were the result of mechanism direction of motion. In life test data from other programs that used toroid type bearings, it was noted that the particular mechanism motion profile included periodic and numerous reversals.

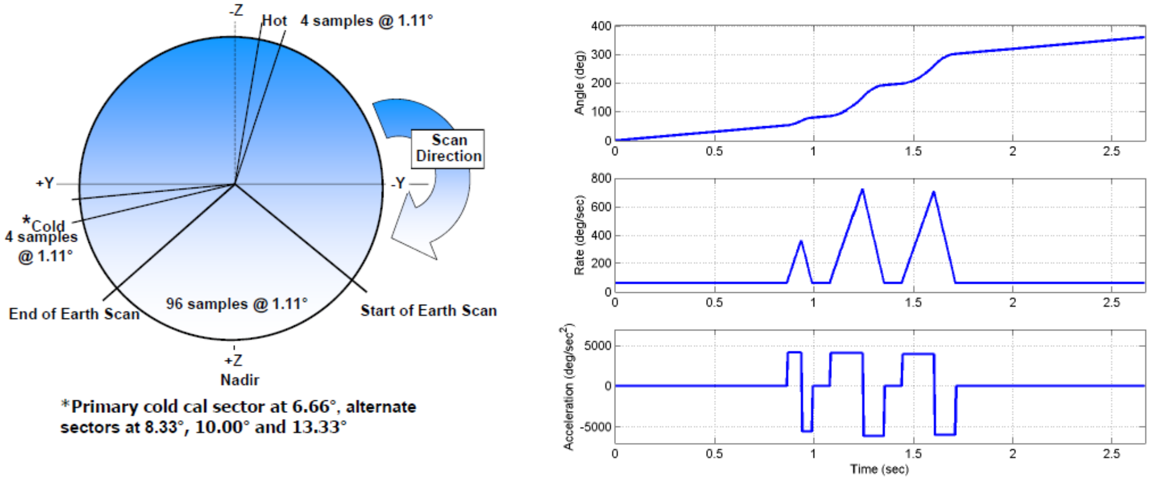
A comparison of the Test Station #2 life test bearing with rotation in one direction and a similar life test bearing that rotated equally in both directions is shown in Figure 5. The bi-directional bearing is clearly in much better condition than the ATMS bearing despite achieving six times the number of revolutions.

Figure 5. Comparison of Test Station#2 bearing with a similar bearing in relatively good condition with equal direction reversals after 6X times the number of revolutions.
Left Figure: ATMS uni-directional test bearing at 63 Mrevs
Right Figure: Similar bi-directional bearing at 362 Mrevs

Reversing bearing rotational direction minimizes toroid wear because it reduces the chance for the toroids to get stuck/pinned in one orientation. The toroid that is pinned by the driving ball will tend to rub in one spot causing the lubricant to dry out and also inhibits the supply of fresh lubricant. The photos of the worn toroids from post-test inspection (see the next section) clearly show that the toroids were locked in one orientation forming ball pocket wear divots. From the steel ring-on-block tests reported in Reference 3 , the wear rate of unlubricated (dry), PTFE test samples was >1000 times the wear rate of those lubricated. This obviously has a major effect on toroid wear life.

The major benefit from reversing direction is that it allows the toroids to reorient due to clearances between the balls and the release of load during reversal. The unloaded toroids have the opportunity to reorient themselves not only presenting a fresh rewetted surface but also distributing wear more equally around the toroid perimeter.

The ATMS bearing application, by comparison, did not involve any reversals in its operation. The ATMS motion profile is uni-directional for the entire life of the instrument. There are accelerations and decelerations in the ATMS profile, but no opportunities for reversal of motion. A description of the ATMS profile is provided in Figure 6. Note that the primary data collect occurs during the Earth scan at constant speed as does the cold and hot calibrations. In order to minimize revisit time to the required 8/3 of a second per revolution, the scanner must accelerate and brake at extremely high levels (4500 to 5000 deg/s^2) three times each revolution. At first it was thought that these high acceleration levels were responsible for ball skidding leading to premature life. However subsequent analysis showed that the dynamic loads were very small compared to the bearing preload making skidding unlikely.



*Primary cold cal sector at 6.66°, alternate sectors at 8.33°, 10.00° and 13.33°

- **Scan Mode**
  - **Constant speed during data collection**
    - **Earth Scan**
    - **Cold & Hot calibration sectors**
  - **Accel / Decel profile between sectors**
- **Stare Mode**
  - **Go to defined position and stop**

Figure 6. ATMS Scan Profile Description

Test Station Bearing Post-Mortem

To gain insight into the mechanism of the toroid wear seen in the original test station 2 bearings, the bearings were removed from storage for a more detailed inspection. Detailed measurements were taken of the surviving toroids and some 3D modeling was performed to gain insight into the mechanics of the wear phenomena. Figure 7 and 8 present an example of one of the surviving toroids and modeling results showing the configuration of the toroids during the wear process.

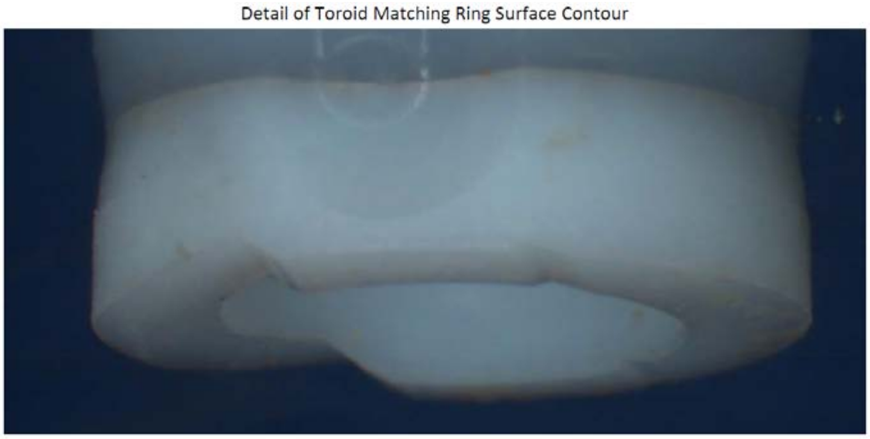

Detail of Toroid Matching Ring Surface Contour

Figure 7. Sample Bearing Toroid – Test Station #2

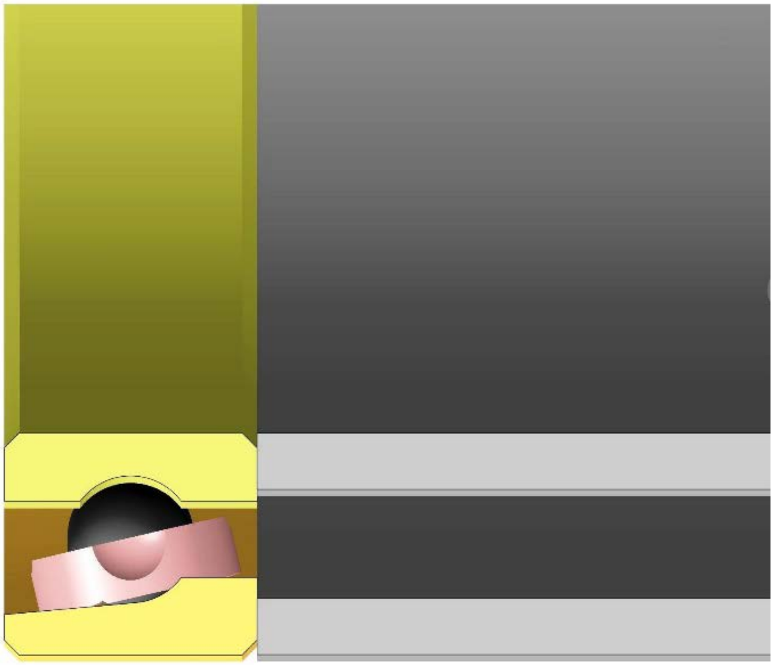


Figure 8. Modeling of Toroid Wear of Sample Pictured in Figure 7 – Test Station #2

The wear patterns noticeable in the test station #2 toroids had a variety of configurations, but the one shown above is most telling. It shows that the bearing races had a significant contribution to the wearing of the toroids. However, the major mode of wear that lead to the destruction of the toroids was the one where the balls wore an ever deepening 'dimple' into the toroid that lead to the disintegration of the circular geometry. In other words, the 'dimple' went so deep that the toroid split in two. Subsequently, the toroid halves were ground up by the continuously rotating bearing elements – thereby causing the current spikes that were observed in telemetry. The grinding up of the toroid material lead to the creation of a slurry of Teflon particles and lubricant outside of the bearings. There were no intact toroids in either of the two bearings from test station #1 indicating the test station bearings were run well beyond their useful lives.

Only a slight indication of residual lubrication on rolling elements was observed. There were also indications that lubricant was creeping out of the bearing assembly forming the slurry observed external to the bearing.

Pre-load of the bearing pair was checked and found to be unchanged if not a little higher than from assembly records. This may have been due to measurement uncertainty or to a very thin film of slurry on the metallic surfaces that minutely changed bearing dimensions.

It should be pointed out that it was anticipated that many of the toroids in test stations 1 and 3 were compromised at this point. However, the units were run to gain experience with running damaged bearings and also to see what benefit might be gained from our mitigation strategy of periodically reversing the motion of the scanner.

For the purposes of showing the variety of the wear patterns of the toroids from test station #2, Figure 9 is offered. The first picture shows a concave toroid wear pattern suggesting that this toroid was rotating and distributing wear around the toroid circumference. The remaining pictures show ball wear pockets indicative of toroids that got stuck in one position accelerating wear

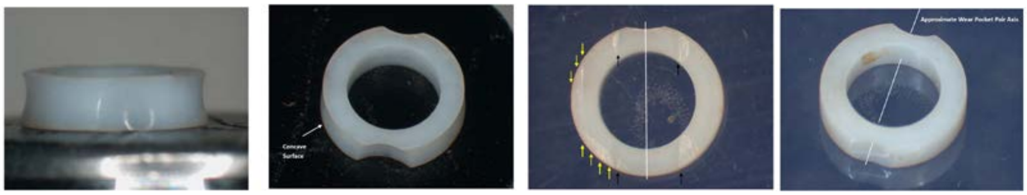


Figure 9. Toroid Wear Patterns (test station #2)

Putting the Puzzle Together

So we had some information suggesting that the on-orbit motor current spikes were similar to the bearing life test station results. Also, we had some 3D modeling results that was able to explain the wear patterns on a sample of the intact toroids. On-orbit motor current data was obtained at a high sampling rate (148 samples/second) that could be used to perform some analyses – including FFT, to get a better understanding of the on-orbit situation. In addition, wear rate analysis was performed that suggested that Teflon wear rate was highly dependent on lubrication of the interfacing surfaces – ball to toroid in this case. Figure 10 shows a sample of an FFT that was obtained from on-orbit data that suggested a response at the Ball Spin Frequency. This was another clue in suspecting an interaction between the bearing ball(s) and its cage (toroid).

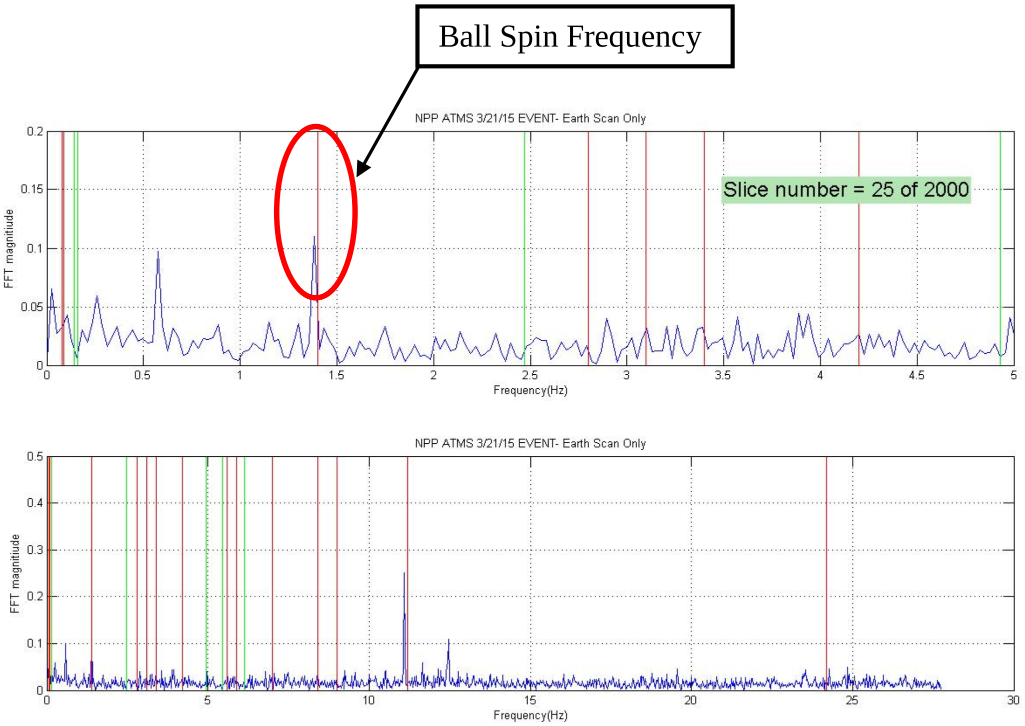


Figure 10. FFT Results showing Ball Spin Frequency response

The end result of all the investigation and analysis lead to the conclusion that the ball toroid interface was running dry. The operation of the mechanism in one direction was not allowing for the re-orientation and hence re-lubrication of those surfaces of the toroids. Thus began a rapidly advancing wear of the softer material (Teflon toroids). As the 'pockets' in the toroids got deeper, the harder it was for any re-orientation of the toroids to occur.

Once the wear mechanism was understood, the effort was turned into one of developing a mitigation that could be implemented on-orbit with minimal impact to the science provided by the instrument. With the experience in hand of another program that used the Teflon toroids successfully, it was suggested that a modified scan pattern be implemented to allow for the re-orientation of the toroids. We looked long and hard at new permutations of the instrument scan profile. Eventually, this lead to the suggestion of doing some limited number of reversals at a point in the spacecraft orbit that would have negligible impact to science. The SNPP science team came to rescue by suggesting that the instrument science would not be significantly impacted if a limited number of reversals were implemented at a high latitude point in the orbit. Eventually, we settled on doing the reversals above 74 degrees North latitude.

Northrop Grumman was tasked to develop and test a command sequence to have the scanner go in a reverse direction. They came back with an elegant and simple process of uploading a new scan profile table that would perform the desired operation. Once loaded, this new table would be enabled by command at a time desired and then another command would be issued to go back to a normal scan table. Northrop Grumman tested this process on their simulator and also on the sensor Engineering Development Unit. Also, after a number discussions and some test information from the still running bearing test stations, we settled on doing six contiguous scans in reverse direction once per day above 74 degrees North latitude.

The six reversals per day were tested on two running bearing test stations at different times. At this period of time, both stations were down because both stalled in late 2014 due to high torque and were shut down pending new engineering direction. The reversal testing was started on test station 3 in April 2015 while test station 1 was restarted in March of 2015 running the normal scan profile without reversals. While test station 3 was being used for reversal testing, test station 1 stalled in early August of 2015. At this point in time we needed to develop more experience with reversals, so we decided to restart station 1 doing daily reversals. At first, test station #1 was reluctant to re-start, but eventually did in mid-August 2015. Test station #1 was run with the daily reversals for about a month before its disassembly. At the time of its test termination, test station #1 was past its 2X mission life. Test station #3 continues to run with good results and is almost at its 2X life point as this is being written. Figure 11 shows the motor current data for test station #3 as of December 8, 2015 and Figure 12 shows the motor current for test station #1.

It is anticipated that the toroids in the test station #3 bearings are compromised to some extent, but no definitive statement can be made as to their actual state. It would be logical to expect that the station 3 toroid condition is somewhere between the states of the disassembled test stations 1 and 2.

The reversals on test stations 1 and 3 were successful in giving these bearings new life. However due to the debris generated by the failure of the toroids, some torque spikes are expected to occur. The toroid debris is being ground up by the action of the balls against the races. It is thought that the reversals arrest the further degradation of intact toroids as contact surfaces are being re-wetted with remaining lubricant.

The on-orbit scanner bearing condition is not thought to be in as dire a condition as the test set #2 and certainly not like test station #1 bearings at past its 2X mission life, but it is conceivable that a number of toroids are missing in the flight bearings. So far the scanner on-orbit is still performing within pointing limits and the bearing torque has returned to near mission-start levels after reversal implementation so our expectation is that toroid damage is not too severe.

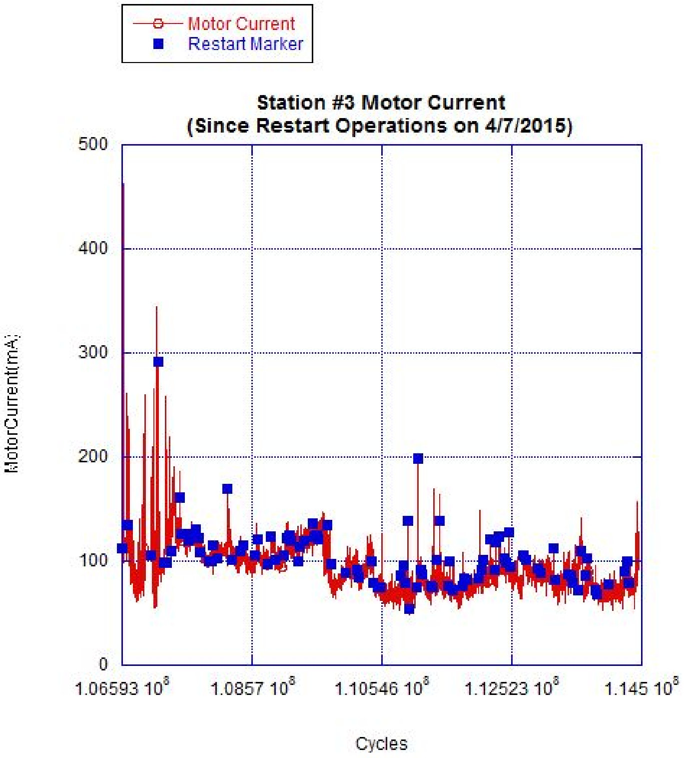


Figure 11. Motor Current of Test Station #3 (12/08/2015) – blue squares indicate reversals

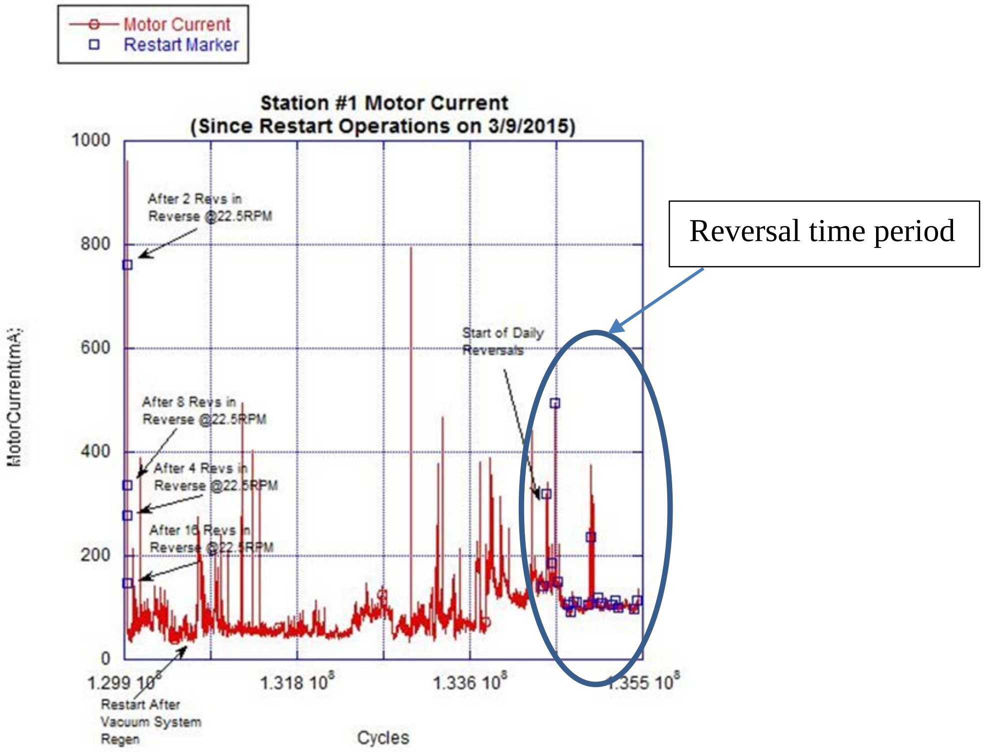


Figure 12. Motor Current of Test Station #1 (9/16/2015) after 11.5 years of equivalent operation prior to disassembly. Note the more stable level of motor current after reversals.

Life Extension Mitigation Implementation

The on-orbit reversal process was initiated on July 14, 2015. It consisted of a table load and its verification and then followed by the first reversal sequence. The first reversals were done by ground command, which put restrictions on how fast people and command systems can operate. This resulted in approximately 26 reverse direction rotations of the scanner before the return of normal forward scan operation. This reversal resulted in a motor current spike that died away after about 3 days, which is faster than previous 'naturally occurring' current spikes. A result like that was anticipated based on bearing test set reversals. The reversal command process was implemented via the spacecraft Daily Activity Schedule command load on August 24, 2015. This simplified the command implementation and had the effect of implementing the reversals as part of normal spacecraft operation – basically making it seamless. It also had the result of fixing the number of reversals at the desired number of six contiguous reversals per day.

Many thanks go out to the people in the satellite control center for their work in developing and testing of the scripts related to the implementation of the reversals.

The daily reversals have been performed without interruption since August 24, 2015. Only one noticeable motor current 'event' has occurred since then and that happened early in the process on August 26, 2015. Since then the motor current has been rather stable with only small perturbations.

Figure 13 shows the transition from reverse and then back to normal. The figure shows the scan angle vs scan telemetry sample number of the dataset. There are 148 data samples per complete scan rotation.

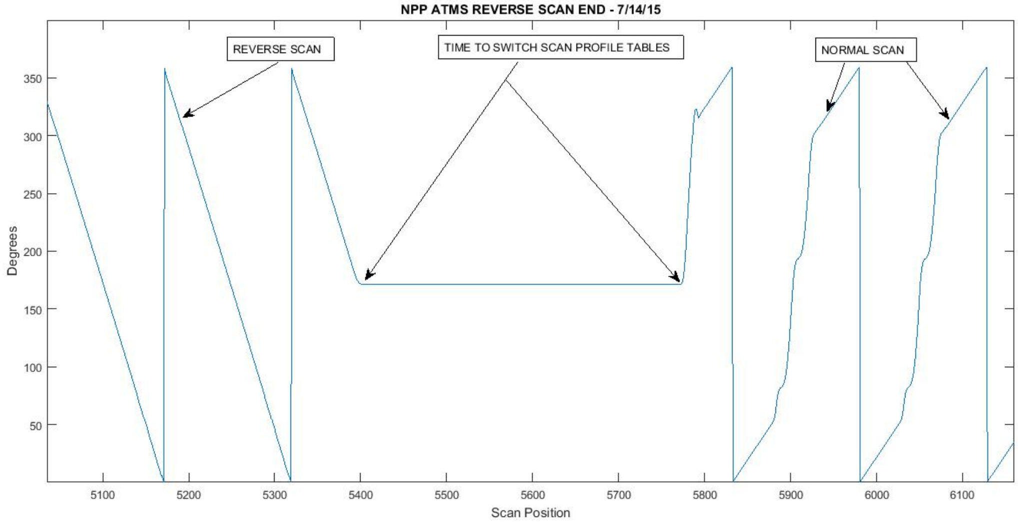


Figure 13. Scanner Recovery from Reverse to Normal Scan

Figure 14 is provided to capture the scanner main motor current for the past year. It should be noted that the motor current level is now at start of mission values. This would indicate that the reversals are effective in re-lubricating the bearing/toroid surfaces. Also, the reversals may allow the toroids to re-orient themselves exposing freshly lubricated Teflon surfaces to contact the adjacent balls.

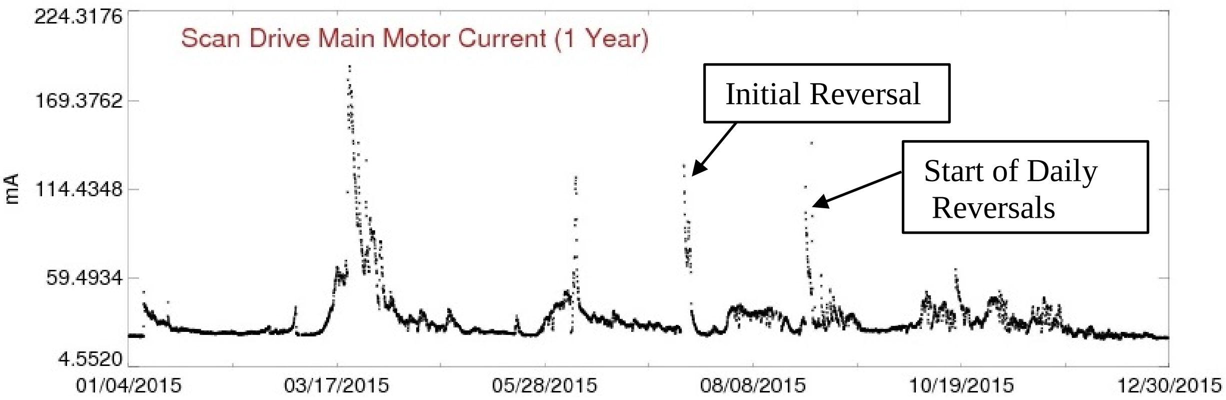


Figure 14. Scan Drive Motor Current 1 Year History

Conclusions

From the years of effort related to the SNPP ATMS scanner bearing system, the following recommendations and observations can be offered:

1) Use of Teflon toroids in space bearing applications has to consider the range of motion of the mechanism. Based on this experience, uni-directional applications for toroid use cannot be recommended. Applications with regular directional reversals may be acceptable and even desirable, but must be based on a good and representative life test program.
2) Uni-directional motion will result in eventual dry running of the toroid/ball interface leading to the premature failure of the toroid separators.
3) Bearing life test programs must use flight like hardware, not only for the bearings but also for the drive motors, encoders, electrical drivers and telemetry sensors. A flight-like Engineering Development Unit of the mechanism in other words. This would allow for a one to one comparison of life test data to on-orbit telemetry. Not doing so, results in a very difficult analysis task of any on-orbit data when anomalies occur.
4) Motion reversals are very effective in preventing or arresting the wear of bearing toroids. It is evident from the bearing test units and on-orbit data that reversals eventually lead to acceptable bearing performance. Depending on the state of toroid wear, initial reversal results may include ‘spiky’ behavior. However, data shows that eventually the bearings settle down into a near normal state. The SNPP on-orbit torque levels are now subsiding to near early orbit values, although with some spiky behavior.

Acknowledgements

Every successful major project results from the combined efforts of many people. It is with great regret we don’t have the space to list all of the many people who contributed time, effort, and talent to the ATMS Scan Drive program. Nonetheless, most of those who participated in the Scan Drive Life Extension program would agree that the following people were key to the success of this effort. Goddard Space Flight Center: Mark McClendon, Chris Hoffman, Robert Lambeck, Bruce Guenther, Jason Sturgis, Tom Manson, Harry Solomon, Tamara Oconnell, Michael Dube, Ed Dobbins, Dan Helfrich; NOAA: Brennan Nowak, Jim Waters, Ninghai Sun; Northrop Grumman Electronic Systems: Mike Landrum, Paul Schan, Victor Jacobo, Kent Anderson; Aerospace Corp: Tina Gentry, Neal Baker, Marc Wigdor, Joe Pope; Lincoln Labs: Vince Leslie

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