PROBLEMS ENCOUNTERED DURING THE RECERTIFICATION OF THE GLORY SOLAR ARRAY DUAL AXIS GIMBAL DRIVE ACTUATORS

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ABSTRACT

The Glory observatory is the current incarnation of the Vegetation Canopy Lidar (VCL) mission spacecraft bus. The VCL spacecraft bus, having been cancelled for programmatic reasons in 2000, was nearly integrated when it was put into storage for possible future use. The Glory mission was a suitable candidate for using this spacecraft and in 2006 an effort to recertify the two axis solar array gimbal drive after its extended storage was begun. What was expected to be a simple performance validation of the two dual axis gimbal stepper motors became a serious test, diagnosis and repair task once questions arose on the flight worthiness of the hardware.

A significant test program logic flow was developed which identified decisions that could be made based on the results of individual recertification tests. Without disassembling the bi-axial gimbals, beginning with stepper motor threshold voltage measurements and relating these to powered drive torque measurements, both performed at the spacecraft integrator's facility, a confusing picture of the health of the actuators came to light. Tests at the gimbal assembly level and tests of the disassembled actuators were performed by the manufacturer to validate our results and torque discrepancies were noted. Further disassembly to the component level of the actuator revealed the source of the torque loss.

1. INTRODUCTION

The Glory observatory will fly a three instrument suite to advance the understanding of aerosols and solar irradiance. The Advanced Polarimeter Sensor (APS) in combination with two cloud cameras will determine the global distribution of natural and anthropogenic aerosols and clouds allowing quantification of direct and indirect effects on global warming. This capability will significantly reduce the current 40% uncertainty of the effect of aerosols in the radiative forcing function. The second primary instrument, the Total Irradiance Monitor (TIM) will provide for continued measurement of solar irradiance to determine the Sun's direct and indirect effect on the Earth's climate. Fig. 1 shows the Glory observatory and a two-axis Solar Array Drive Assemblie (SADA). The SADAs are configured in a pan – tilt (alpha under beta) orientation.

Figure 1 Glory Observatory and the Solar Array Drive Assembly

In 2003, the Glory pre-program study phase identified the nearly completed spacecraft bus from the VCL observatory program as a viable option for accommodating the Glory instrument suite. Among many components that weathered the three year storage period between VCL cancellation and Glory program startup were the SADAs. As the SADAs were originally delivered in 2000 they will be approximately 9 years old once they are finally on-orbit in late 2009.

While in storage the VCL bus was properly housed in a sturdy container with an inert Nitrogen cover gas. Nevertheless, the SADAs were thus identified as having a level of risk due to their age particularly with the uncertainty associated with how the Pennzane lubricant may have migrated or degraded during the long dormant period. In addition, the revised spacecraft configuration requires driving the solar arrays in a higher inertia configuration at higher speeds, raising additional questions about the output torque capabilities in terms of torque margin.

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2. SADA RECERTIFICATION TEST PROGRAM APPROACH

The test approach evolved during the fall of 2006 with the intent of measuring basic performance characteristics of the two stepper motors in each of the two SADAs for comparison against their baseline data recorded in year 2000. The original approach was to ship the SADAs back to Moog Chatsworth Operations, the manufacturer of the SADAs, for test. However, several programmatic factors eventually led to a decision to perform SADA retesting and verification at Orbital Sciences Corp.

The original performance characterizations at Moog's facility were measured at the individual actuator level before assembling the two actuators (alpha and beta) into the completed biaxial gimbals. Except for direct output torque measurements, all the actuator performance measurements could be performed by Orbital at the biaxial gimbal level. With special fixturing, beta actuator output torque could be measured directly. Assessment of alpha actuator torque performance would have required separation of the biaxial gimbals into separate actuators which was beyond the scope and risk Orbital was willing to bear. Accordingly, the test program was designed to use the past (year 2000) and present (2006) alpha threshold voltage measurements as an assumed bridge for validating torque capability.

Threshold voltage is a measure of the design margin the motor has to start without losing synchronization. The threshold voltage measurements were understood to be a measure of whether or not actuator internal losses were normal/in-family. The logic, **thought now to be flawed**, was that if the threshold voltage measurements of the alpha and beta actuators were both within a small fraction of the baseline values and the torque capability of the beta actuator was similarly consistent then the torque capability of the alpha actuator could be assumed to be satisfactory as well.

3. TEST SETUPS AND INITIAL TEST RESULTS

Fig. 2 shows the electronics interface test schematic, and the predicted oscilloscope plots. The test depended on being able to use the Glory flight Electronic Drive Unit (EDU) which has a normal input voltage range of 22 to 35 volts. Voltage can be reduced below 22 volts but internal power supply and control circuits require about 16 volts to function properly. This is much greater than the baseline 7 to 8 volts across the windings required to initiate and sustain movement of the actuators (i.e. threshold movement). For this reason the normal voltage range had to be furnished to the EDU and the external circuit dropping resistors shown in the schematic were used to drop the output voltage across the windings. The fixturing for threshold voltage testing was such that both actuators were free to turn. Tab. 1 shows the threshold voltage test results. Inspection of these results shows that the new threshold voltage results were in-family with those recorded by Moog in 1999/2000. At this point it appeared testing would soon result in SADA re-certification for flight.

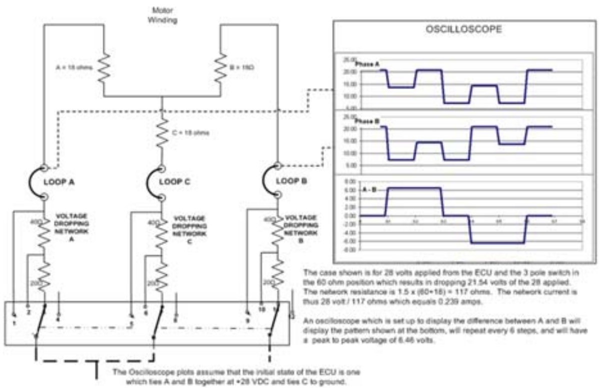

Figure 2 Threshold Voltage Testing

Fig. 3 shows the setup for ambient torque testing at full flight driver voltages. The test arrangement included a Himmelstein torque transducer and a Planetrol gear reducer to amplify the effect of the Placid Industries hysteresis brake. Flexible couplings and careful alignment ensured there were no misalignment induced torque errors. The torque versus time plot of Fig. 4 shows a typical loss of synchronization (torque dropout). The simultaneously generated position versus time plot shows the same dropout. The objective was to find a brake induced torque resistance which the

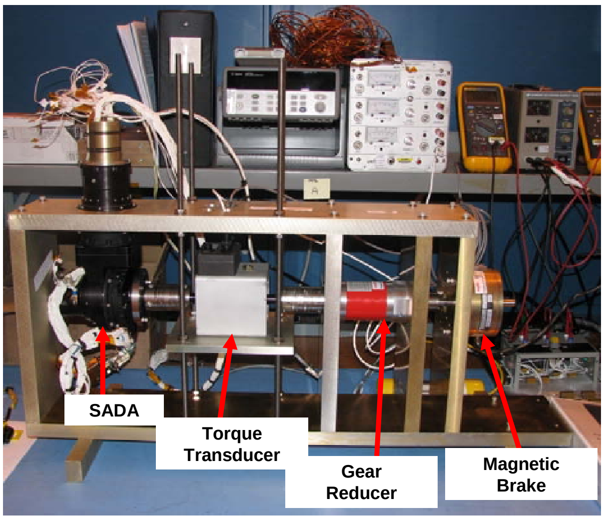

Figure 3 Torque Test Setup

Table 1 Threshold Voltage Measurements in 1999/2000 (Moog) and 2007 (Orbital)

	SADA 1				SADA 2			
	Alpha		Beta		Alpha		Beta	
	Moog	Glory	Moog	Glory	Moog	Glory	Moog	Glory
Threshold Volts								
CCW Ambient	7.14	6.86	7.42	7.38	7.22	6.89	7.24	6.82
Hot	7.59	7.60	7.59	8.11	7.61	7.60	7.66	7.66
Cold	6.57	6.48	6.57	6.83	6.37	6.51	6.55	6.59

actuator could drive through the entire range of motion. This was defined as the actuator's torque capability at the particular operating speed utilized.

Torque capability in the 150 in-lb to 190 in-lb (16.9 N-m to 21.5 N-m) range was produced prior to shipment but, as demonstrated by the plots in Fig. 4, there was either 30% degradation in torque or a serious flaw existed in the test apparatus. At least two days were spent checking the calibration of the torque test setup. The final test results for both SADAs are shown in Tab. 2. In this table, "N/A" indicates the configuration could not be tested without disassembly.

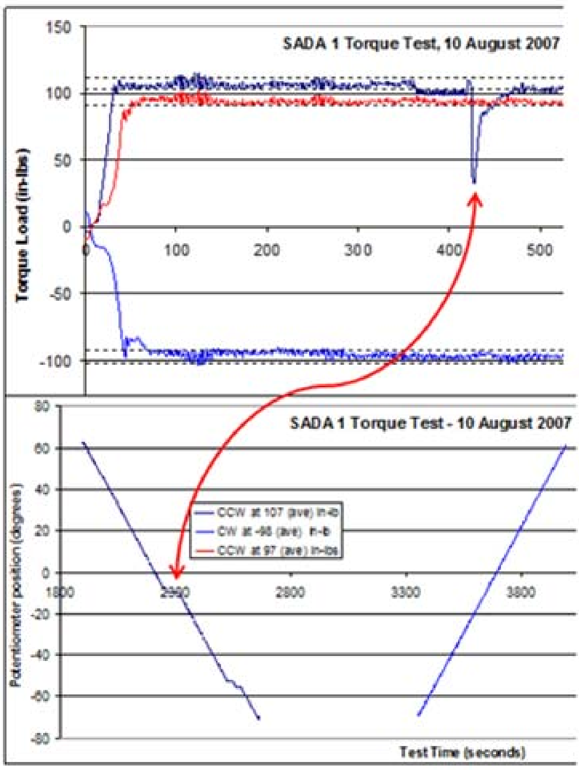

Figure 4 Torque Test Data

According to our calculations, the threshold voltage test should have had sufficient sensitivity to detect internal loss changes on the order of 30%. This mysterious torque loss was very perplexing. Moog was contacted to validate our torque testing approach, and they did validate it. Despite test setup confirmation indicating our torque measurement approach was not flawed, the sentiment at the time was that something was amiss with the setup and that the SADAs were, most likely, acceptable. A large contributor to this sentiment was the fact that the threshold voltage measurements were very reassuring. Nevertheless, NASA and Orbital agreed to follow the logic flow of our recertification decision tree and send the units back to Moog for a set of confirmation tests. At the time, it was assumed that some detail of the test setup or apparatus was flawed and that the inconsistency between the threshold test data and the torque test data would be resolved when Moog retested the actuators using the original test equipment.

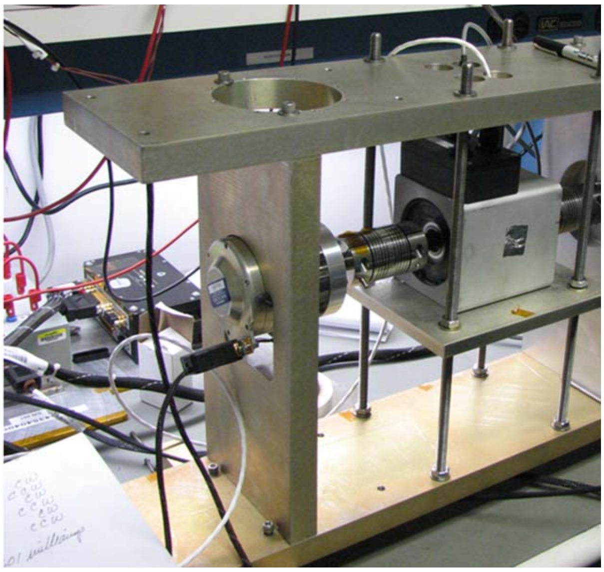

Figure 5 Moog Test Actuator Mounted in Altered Glory SADA Test Apparatus

NASA, Orbital and Moog worked together closely and an approach was quickly derived to carefully measure the torque of a non-flight test actuator at Moog's facility

Table 2 Torque Measurements in 1999/2000 (Moog) and 2007 (Orbital)

	SADA 1				SADA 2			
	Alpha		Beta		Alpha		Beta	
	Moog	Glory	Moog	Glory	Moog	Glory	Moog	Glory
Torque CW								
Moog @ 17 VDC	152		156		160		156	
Moog @ 32 VDC	152		164		160	NA	184	
Glory @ 28 VDC		NA		111				157
Percentage lower than Moog min.			-29%				-15%	
Threshold Volts								
CW Ambient	7.33	7.09	7.04	7.26	6.67	6.70	7.06	6.94
Hot	7.84	7.93	7.84	7.96	7.24	7.22	7.24	7.65
Cold	6.70	5.59	6.70	6.61	5.95	5.94	6.51	6.50
Torque CCW								
Moog @ 17 VDC	172		168		180		188	
Moog @ 32 VDC	176		176		184		188	
Glory @ 28 VDC		NA		113		NA		145
Percentage lower than Moog min.			-33%				-23%	

using their test equipment but testing across the entire range of operation in the way Orbital had tested the SADAs. While this was accomplished at Moog, Orbital adapted their torque test setup to accept the Moog test actuator shown in Fig. 5. The Orbital torque results for the test actuator were in close agreement with those from Moog indicating approximately 30% torque loss and thus adding even more concern that the SADAs had, in fact, degraded over the past several years of storage and occasional use with Glory integration and test activities. The original test program was completed and an executive test summary written to document the results.

4. INERTIA TESTING

While not part of the original test plan, inertia testing was added to the test program because there was concern that the speed of 2^{o}/sec available for resetting the solar array positions during eclipse might be too fast. As such, the actuators could lose synchronization and lose steps or possibly stall. The test setup used for inertia testing was similar to that shown in Fig. 3 except that the brake was replaced with a solar array inertia simulator as shown in Fig. 6. A typical plot of angular position from the actuator potentiometer (the secondary was usually used) versus time is shown in Fig. 7.

The inertia used in this test setup was 150% of the solar array inertia that the Alpha actuator will be required to drive during each orbit. The inertia wheel consisted of 6 masses which could be positioned using threaded spokes to adjust inertia. While the test increased confidence that the inertia can be started at 2^{o}/second the amount of backlash in the test system precluded complete certainty of that conclusion. The majority of backlash was attributed to the test setup gear reducer and not in the SADA itself. The presence of backlash is non-conservative with respect to starting the inertia because more time is available for the momentum to increase which means the torque required from the actuator can be lower.

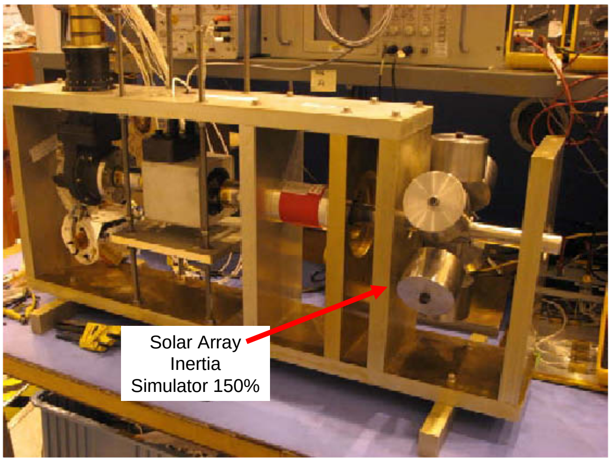

Figure 6 Inertia Testing Setup

To achieve a more conservative, test the actuator speed was increased to 4^{o}/second and then 6^{o}/second. In all cases the inertia was started without any lost steps. Additional test were conducted with the backlash manually removed by pre-rotating the inertia load prior to starting the actuator at 2^o/second.

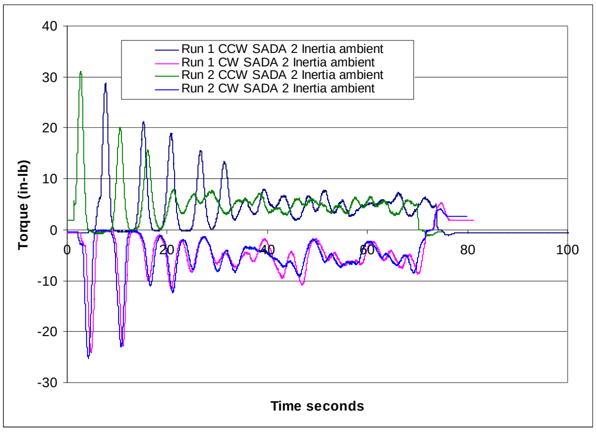

Figure 7 SADA 2 Inertia Test Record

5. FAILURE INVESTIGATION

The test services agreement with Moog was expanded to include return of the worst case SADA S/N 1 to Moog for testing followed by SADA S/N 2 if the torque findings continued to evidence degradation. This was a small part of a detailed test strategy, which is shown in Fig. 8.

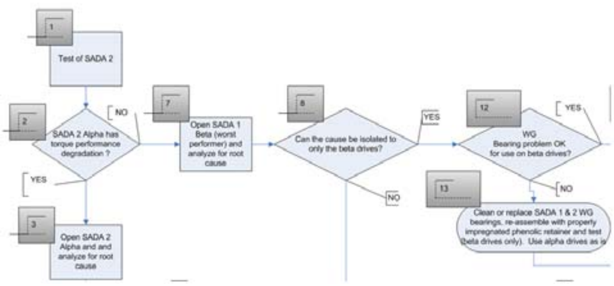

Figure 8 Initial Steps in a Detailed Test Strategy

SADA 1 was returned to Moog in January 2008 and subsequently tested with the following activities and observations:

a. The alpha drive showed no degradation from 1999.
b. The beta drive showed the 30% to 40% degradation measured by Orbital.
c. The SADA 1 motor stator housing was removed allowing the rotor/harmonic wave generator to remain installed. Moog observed that rotor rotation was 'lumpy' with repetitive cyclic torque peaks of approximately 6.5 inch-ounces (45.9 mN-m) versus the Moog requirement for new hardware of 2 inch-ounces (14 mN-m).
d. There remained a good quantity of grease/oil slurry present in the wave generator bearing.
e. The amber colored lubricant inside the harmonic drive wave generator bearing was somewhat darker in places than the shade for new lubricant (50% Pennzane oil & 50% Pennzane grease).
f. The cleaned wave generator bearing races had small patches of discoloration with a grainy appearance from either embedded material or a divot. These are shown in Fig. 9. Three such patches on each side were located on the inner race at the major diameter areas and coincided with the spacing of the balls. The remaining portions of the races were clean and smooth. An attempt was made to mechanically remove the discoloration using a pointed plastic stick but this was not successful.

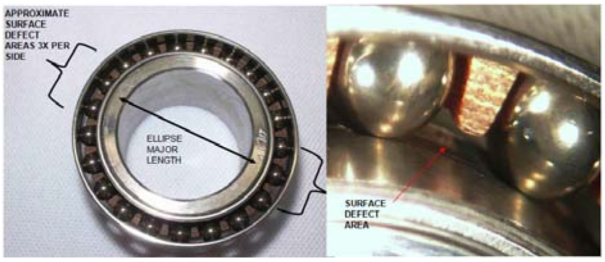

Figure 9 Harmonic Drive Wave Generator Bearing with Defect Areas

SADA 2 was returned to Moog and retested on 1/30/2008. The beta drive showed 20% to 30% output torque degradation. The beta actuator was disassembled and showed the same discolored areas shown in Fig. 9, but not quite as prominently. Prior to disassembly the actuators were subjected to both threshold voltage and torque testing for comparison with the results recorded earlier by Orbital. <u>These results also placed in question the validity of using threshold voltage testing as a conclusive verification that all is well with an actuator.</u>

At this point the flow path led NASA, Orbital and Moog to the decision to disassemble the wave generator bearings from the beta actuators and subject the races and balls to laboratory testing. After two separate investigative sessions at Seal Laboratories, Moog's assessment was that the discolored areas were, in fact, pitted areas most likely due to stress corrosion. Fig. 10 shows a visual summary of the typical findings. Except for a very minor amount of discoloration observed on the alpha actuator of S/N 1, the alpha bearings looked good – but the fact that there was even a small amount of discoloration made them suspect.

6. ROOT CAUSE DETERMINATION

Moog determined that the harmonic drive supplier had used a chlorinated solvent as part of the cleaning process. This practice has long since been prohibited but at the time the VCL SADA components were manufactured the process was still in use. It is thought that some small amount of this solvent had not been fully washed away. This in combination with the presence of sodium in the grease thickener provided the constituents for a salt solution only awaiting the arrival of small amounts of water vapor, the presence of oxygen, and, lastly, the availability of lots of time for the corrosion process to attack the bearing surfaces under most stress. The elliptical wave generator plug provided the stress. The evidence for the presence of chlorine and sodium is shown in the electron dispersion spectrographic (EDS) analysis portion of Fig. 10. Until 2004, the SADAs were stored with the VCL bus bagged and with an N2 cover gas but it was never confirmed that the cover gas had not dissipated, that the bag was entirely leak tight, or that trace amounts of moisture did not exist in the purge gas. In addition, after 2004, the SADAs were exposed to the atmosphere as they were required for integration and test purposes. There remains the mystery as to why the alpha actuators were not nearly as degraded as the beta actuators. Nevertheless, the **root cause** was concluded to be stress corrosion due to the incomplete cleaning of the harmonic drive components leading to the presence of small amounts of chlorine, sodium, water vapor, oxygen, and lots and lots of time.

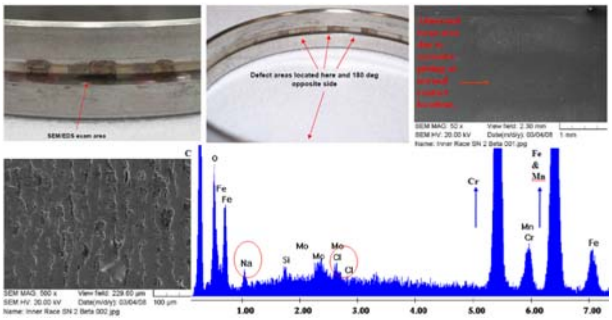

Figure 10 Laboratory Investigation Findings

7. REASSEMBLY AND TEST

Based on the aforementioned findings, Orbital revised the Moog service agreement to include complete replacement of all harmonic drive bearings in both SADAs 1 & 2. While not contributing to the degradation the cotton phenolic wave generator bearing retainers were vacuum impregnated using an extended time of 3 days as recommended by the NASA engineering team. The individual actuators were reassembled and subjected to a complete series of acceptance tests including two axes of vibration and two thermal vacuum cycles. The actuators were received at Orbital in early June 2008 and integrated onto the Glory observatory in early July. Fig. 11 shows the SADAs successfully integrated onto the Glory observatory during solar array deployment testing.

8. LESSONS LEARNED

- A little electrolyte, a little oxygen, and lots of storage time can lead to a problem.
- Retesting mechanisms after a long storage period (several years) is highly recommended.

Figure 11 SADA Integrated onto Glory during Solar Array Deployment Testing

- Use careful controlled storage with an N2 cover gas and periodic sampling when storing sensitive mechanisms for extended periods.
- The mechanisms community needs to take a more careful look at the use of threshold voltage testing – it didn't appear to be predictive for the Glory SADAs.
- "Engineering curiosity" and vigilance are critical attributes to cultivate in the act of problem solving.

9. CONCLUSIONS

As of June 2009, the Glory SADAs continue to operate nominally as the Glory Observatory continues forward towards launch. The SADA test program lasted a total of 14 months from the first day of retest at Orbital (April 2007) until receipt of the refurbished SADAs from Moog (June 2008). From a pragmatic standpoint it would have been better to have sent the SADAs back to Moog as soon as it was decided that re-verification was required. However, the overall experience gained working more intimately with these interesting components and later working with the professionals at Moog was as stated in a popular advertisement, “Priceless”. It is felt that our organization’s (NASA) ability to specify, procure, and operate these mechanisms have been enhanced. The authors are also reminded of the importance of vigilance with respect to processing and contamination control at the component and Observatory levels as well as the importance of maintaining good documentation for potential use when problems arise.

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