GOES-R GN&C CAPABILITIES USED TO SUPPORT INSTRUMENT ANOMALY INVESTIGATIONS

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ABSTRACT

The Geostationary Operational Environmental Satellite-R program (GOES-R) has launched three of the latest generation of US geostationary weather satellites, of which all three are now fully operational. In this paper we discuss how the robust capabilities inherent in the design have been used to address off-nominal instrument performance observed in flight, and to subsequently provide acceptable data return from two of the instruments exhibiting off-nominal performance. The primary science instrument, the Advanced Baseline Imager (ABI), performed well on GOES-16, but on GOES-17 ABI exhibited anomalous infrared (IR) imaging early in the mission. Lower thermal control performance than designed produced elevated temperatures on the IR detectors. This paper presents spacecraft operations undertaken to calibrate the off-nominal performance of the instrument thermal control, and to develop spacecraft operational mitigation steps to recover near-nominal instrument performance. On GOES-16, the magnetometer (MAG) instrument performance was less than expected. As part of the MAG performance investigation, an improved calibration procedure was developed that required use of the entire GOES-R performance envelope. This paper presents an overview of the MAG performance issues and discusses details of the Guidance, Navigation, and Control capabilities employed to help maximize science return.

1 INTRODUCTION

The Geostationary Operational Environmental Satellite (GOES) program has a fully operational constellation of three next-generation GEO weather satellites from the GOES-R series. In the GOES-R series of spacecraft, GOES-16 launched in November 2016, GOES-17 launched in March 2018, and GOES-18 launched in March 2022. The GOES-R spacecraft provide dramatic improvements in GEO weather observation capabilities over the previous generation [1]. The GOES-R spacecraft include both Earth observing and space weather observing instruments, as shown in Figure 1.

Once on-station the GOES-R vehicles undergo Post-Launch Testing (PLT) for several months. During the respective PLT testing campaigns, the GOES-17 ABI instrument exhibited off-nominal performance, and the GOES-16 MAG instrument exhibited off-nominal performance. In this paper we present how the robust Guidance, Navigation, and Control (GN&C) architecture was utilized to investigate the anomalies and to provide effective mitigation strategies to achieve the best possible instrument performance.

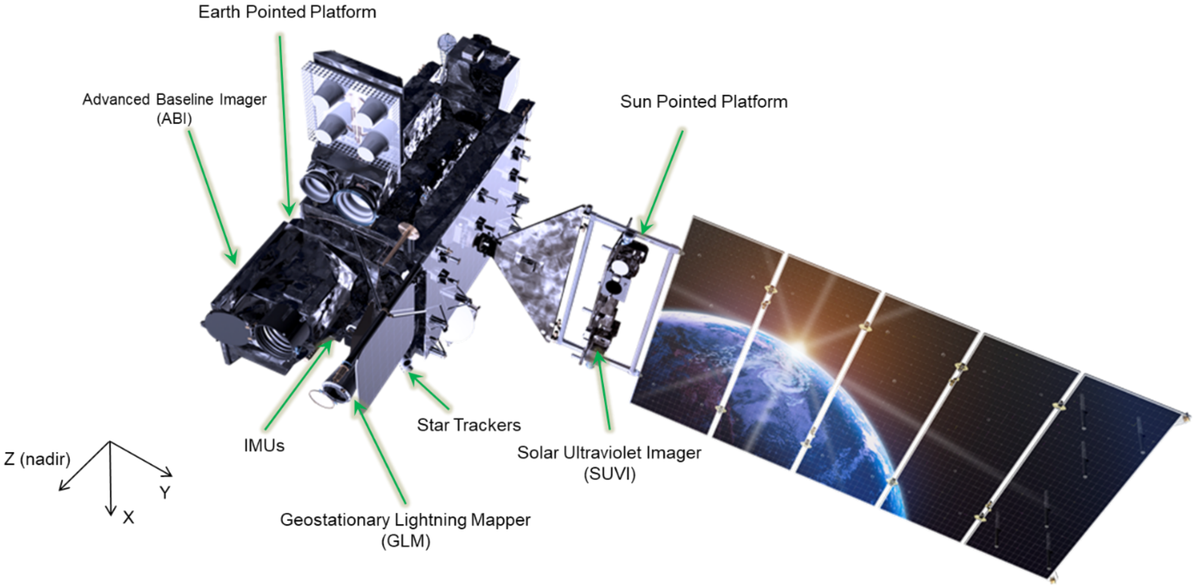
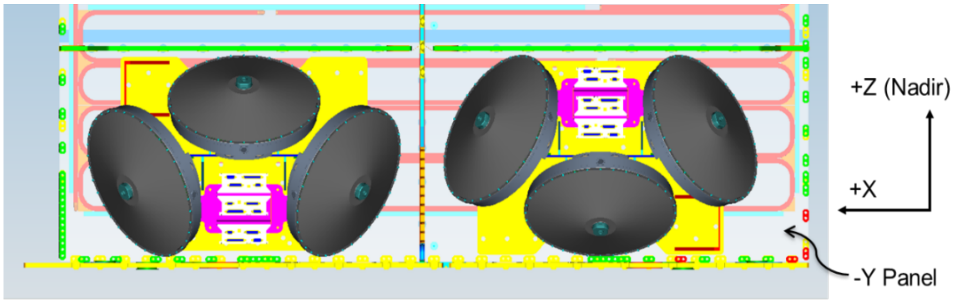


Figure 1. GOES-R Spacecraft in Operational Configuration

Because of the stringent pointing and pointing stability requirements, and because of the operate-through requirements levied by the program [2][3], the GOES-R GN&C design includes features not typically found on GEO spacecraft [4][5][6]. These proved beneficial in assessing the instrument anomalies discussed in this paper and providing the robustness necessary to incorporate mitigations. Particularly important was the reaction wheel configuration, shown in Figure 2. The design includes 6 large reaction wheels, with each rated at 69 Nms momentum capacity at 2600 RPM and 0.38 Nm torque capability. The Markley L-infinity (Linf) algorithm [7] is used to minimize the maximum wheel speed, allowing 33% more momentum storage capacity than a pseudo-inverse solution. It also provides 33% more torque than a pseudo-inverse solution. Simulated and in-flight results of reaction wheel momentum are shown in Figure 3 for a 24-hour period. Significant momentum is accumulated over 24 hours because of the single-wing design, which requires daily momentum dumps to manage the wheel speeds. A biased momentum adjust maneuver can be seen in the middle of each plot.

Reaction Wheel Configuration



Geometric Representation of Reaction Wheels

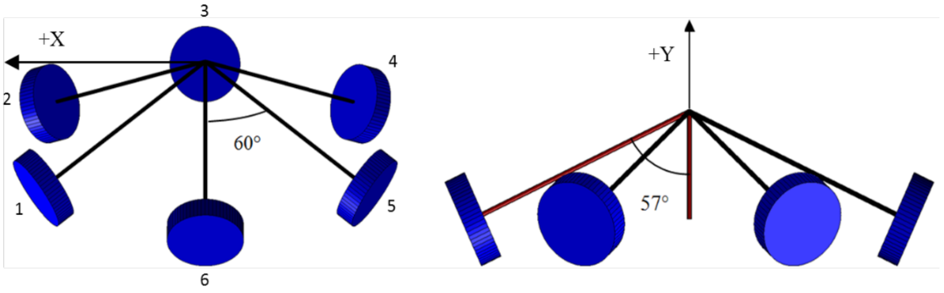
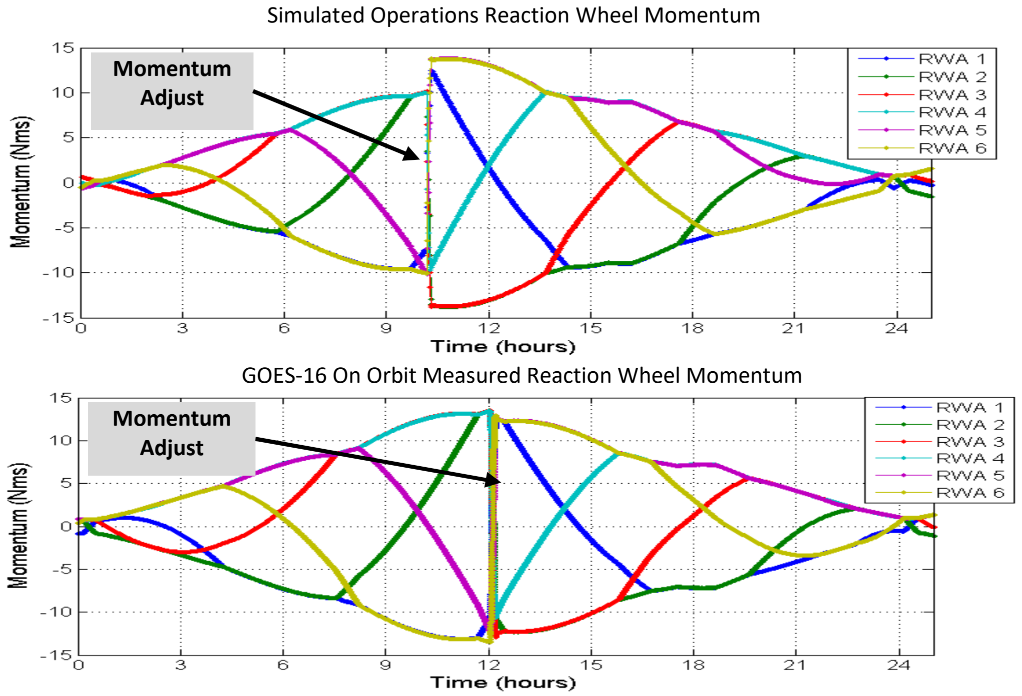


Figure 2. Reaction Wheel Configuration for the GOES-R Spacecraft


Simulated Operations Reaction Wheel Momentum

GOES-16 On Orbit Measured Reaction Wheel Momentum

Figure 3. Daily Reaction Wheel Momentum Profiles (Simulated and In-Flight)

The reaction wheel momentum capacity is significantly less than the normal rated capacity of 160 Nms in order to increase the torque capability to 0.38 Nm. The minimum and maximum torque and momentum capabilities for the 6-wheel suite and the Linf control algorithm are shown in Table 1.

Table 1: Torque and Momentum Capacity of the GOES-R Implementation

Metric	**Momentum (Nms)**	**Torque (Nm)**
Max Body Momentum/Torque:	**233**	**1.27**
Max X-Z Plane Momentum/Torque:	**233**	**1.27**
Min Body Momentum/Torque:	**181**	**0.99**
Min X-Z Plane Momentum/Torque:	**201**	**1.10**

2 GOES-17 ABI PERFORMANCE ANOMALY

This section describes the GOES-17 ABI Loop Heat Pipe (LHP) performance issue, the investigation steps undertaken by the spacecraft, instrument, and NASA teams, and the modified instrument accommodations provided by the spacecraft to help maximize science return.

2.1 Overview of ABI Loop Heat Pipe Anomaly

The GOES-17 ABI instrument exhibited anomalous performance shortly after starting the PLT instrument calibration activities. The ABI instrument includes 16 channels of visible through longwave infrared imagery needed for weather forecasting, volcanic ash monitoring, low cloud/fog monitoring and air-quality monitoring. The visible channels performed nearly flawlessly, just as they had on GOES-16. However, the infrared channels did not perform as expected. The infrared channel detectors must be cooled to ~60 K for the detectors to operate with full performance. To achieve low-temperature detector operation the ABI design includes two cryocoolers, primary and backup. The cryocoolers are connected to the instrument radiator through an LHP. Unfortunately, anomalous loop heat pipe operation was observed shortly after the loop heat pipes were commanded to start. The LHP that should have transferred heat from the instrument to the radiator was performing far below expectations. Furthermore, for specific Sun-relative geometries of the ABI instrument with Sunlight in the ABI optical aperture, the internal ABI temperatures rose to unsafe levels. Emergency steps were undertaken to prevent permanent damage to the ABI instrument, and the failure investigation began immediately. Without the LHP working properly, the infrared channels (13 of the 16 detectors) were unusable for large portions of the GOES-17 orbit. Without mitigation, this would have dramatically reduced the mission capabilities.

2.2 ABI Loop Heat Pipe Performance Characterization

The ABI instrument team attempted to start the LHP operations over a month-long period, with limited success. While this team continued their investigation into the loop heat pipe anomaly and possible mitigations within the instrument itself, a second team was formed to develop operational mitigations from the spacecraft side. The spacecraft team pursued the operational mitigations in two phases: 1) characterization of the worst-case thermal conditions for ABI operations, allowing the ABI team to pursue instrument mitigations, and 2) operational changes for the spacecraft to reduce the thermal loading on the ABI instrument, allowing more operating flexibility for the ABI team.

Thermal analysis predicted that the worst-case orbit for the ABI instrument would occur on August 30th. Because of the urgency associated with the performance anomaly, the program directed the team to perform an in-flight assessment of the worst-case orbit geometry prior to August 30th. To characterize the thermal response for this specific day, the Sun-relative geometry had to be replicated on an earlier day. July 25-26 was selected for the test, which simulated a Sun declination change of 10.8 deg compared to August 30th, as shown in Figure 4. To replicate the thermal conditions for the later orbit day, a 48-hour "relative slew" was selected to implement the proper Sun-relative geometry for the spacecraft. This simply rotates the vehicle about a specified inertial vector with a specified angular rate. The gimbal control implementation replicates the Sun-relative appendage orientations for August 30th as well (the solar array and the Sun-pointed platform). By using this approach, the Sun-relative geometry was within 0.15 deg of the desired geometry for this date, which was more than adequate to assess the instrument and spacecraft thermal conditions.

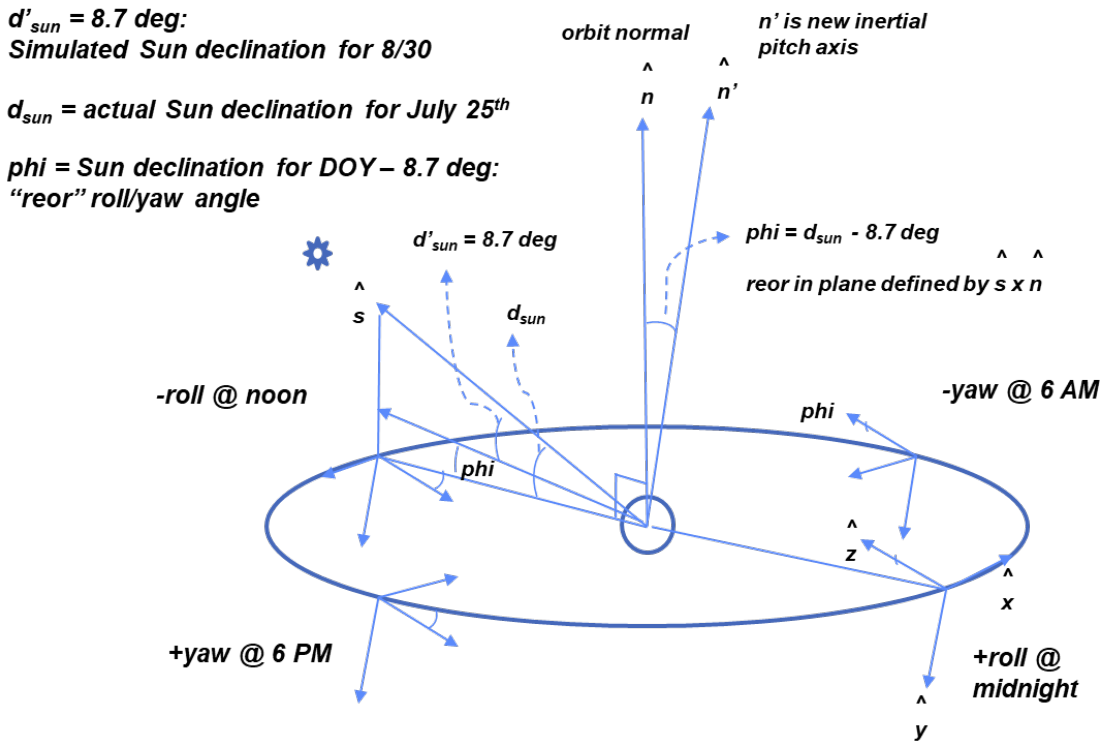


Figure 4. Orbital Geometry Comparison for ABI Thermal Characterization Test

A key complication of this special calibration is associated with the X-band reflector pointing: the earth-relative geometry would not be fixed as is the case for nadir-pointed GEO operations, and the X-band reflector would need to be repeatedly commanded to maintain X-band downlink. The instrument calibration data was only available over the X-band link, so the link needed to be functional for this activity. To maintain the X-band reflector to within 0.1 deg of the ground station, a command sequence was implemented with 288 gimbal position changes over the 48 hours. The resulting 2-axis gimbal profile for the X-band reflector is shown in Figure 5. As expected, most of the motion is about the X-axis of the spacecraft (the "roll" axis), because the spacecraft is no longer rotating about the Earth's north axis. This variation can be seen in the spacecraft's Z-axis variation relative to the nadir vector, shown in Figure 6. The Z-axis varied up to 10.8 deg from the mission's nominal nadir-pointing.

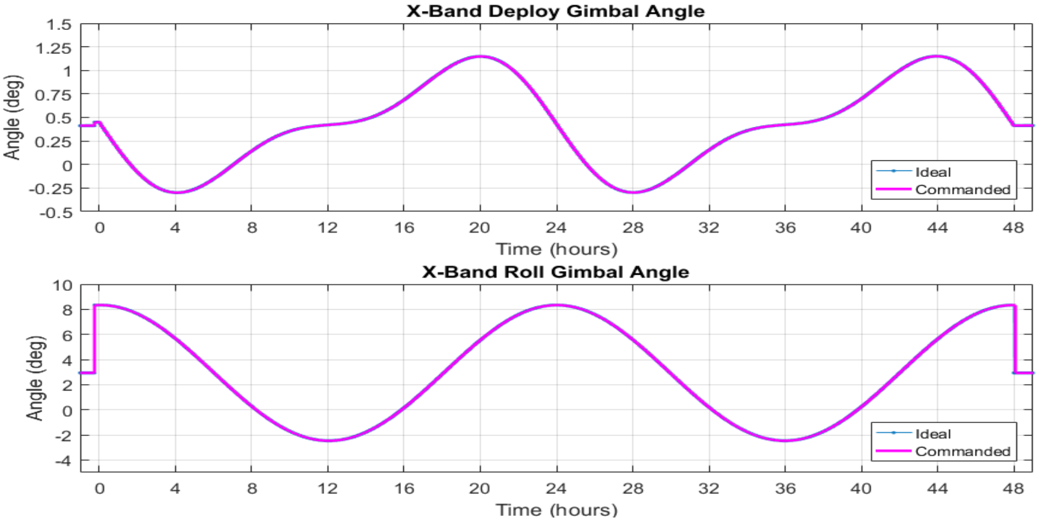


Figure 5. X-Band Reflector Gimbal Profile During Calibration

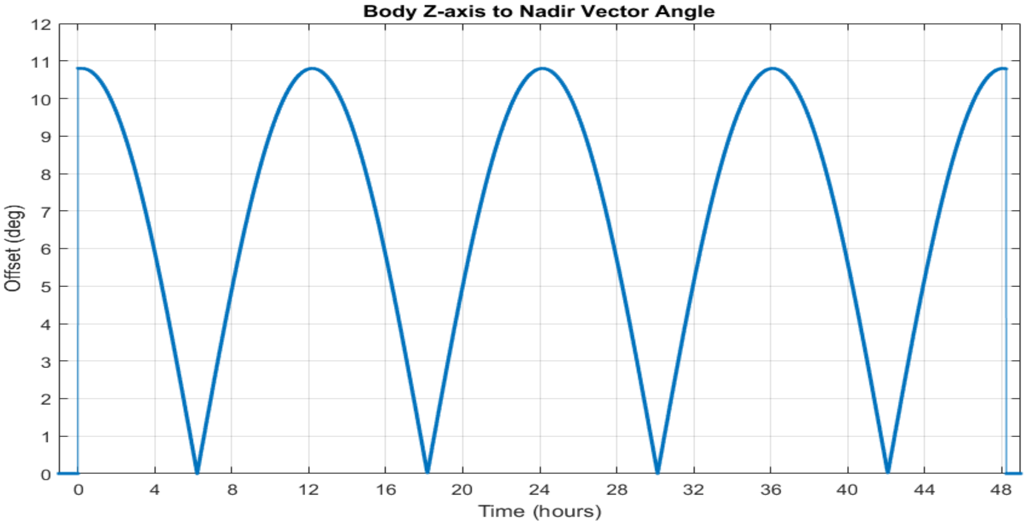


Figure 6. Nadir Vector Varies up to 10.8 deg from Nominal Nadir-Point During Calibration

2.3 ABI Loop Heat Pipe Anomaly Mitigation

The test results firmly established the worst-case thermal conditions for the ABI instrument and enabled thermal-model validation. Using the derived ABI thermal model, analysis results indicated a significant decrease in ABI solar heating could be achieved by keeping Sun on the spacecraft side designed to be pointed north (-Y-axis). The "north" side would normally be the side opposite the solar array in Figure 1. The GOES-R spacecraft design includes a yaw-flip capability, which allows GOES-

17 to fly “upright” or “inverted.” By implementing a yaw flip every 6 months to maintain the Sun on the -Y side of the spacecraft, the internal ABI temperatures could be significantly reduced. In-flight testing of the yaw flip demonstrated a reduction of 10 K for the ABI detectors. This dramatic reduction in temperature greatly increased the availability of the infrared detectors to provide useful data.

The ABI team examined additional strategies to improve thermal control performance, including changes to cryocooler operation. The ABI design includes redundant cryocoolers to mitigate potential failures. Simultaneous operation of both primary and backup cryocoolers was never considered an operational configuration, but the anomaly investigation showed that operating both cryocoolers was much more efficient at removing heat from the detectors. Cryocoolers are a significant jitter source and operating two cryocoolers significantly increases the disturbance environment. Single cryocooler jitter performance has been previously reported for GOES-16 [6][8]. Fortunately, the GOES-R design includes significant design margin relative to the jitter requirements, and the jitter response at the instrument mounting interface for GOES-17 is still within requirements with both cryocoolers operating. This is shown in Figure 7.

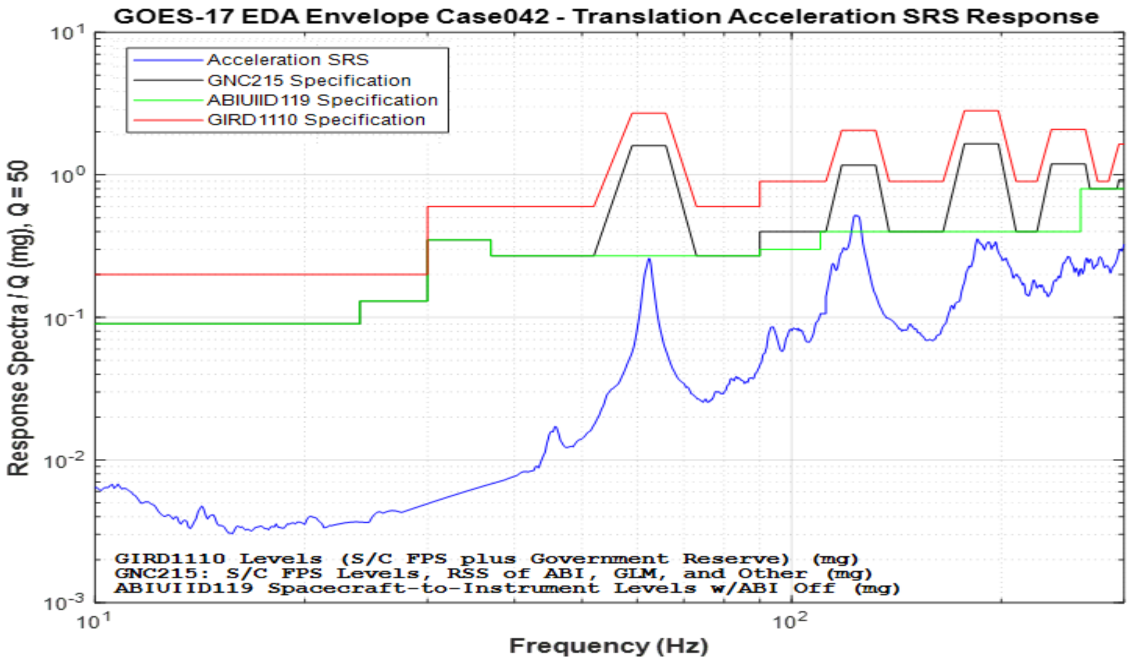


Figure 7. GOES-17 Jitter Response w/ Primary Cryocooler Operating at 62.6 Hz and Redundant Cryocooler Operating at 61.6 Hz.

The ABI team continued to refine the instrument operations to improve infrared detector availability. Although the ABI thermal system is operating at ~5 percent of design capacity, the GOES-17 team has effectively implemented mitigations so that ABI can return 97 percent of its intended data [9]. The effectiveness of the anomaly mitigations can be seen in Figure 8.

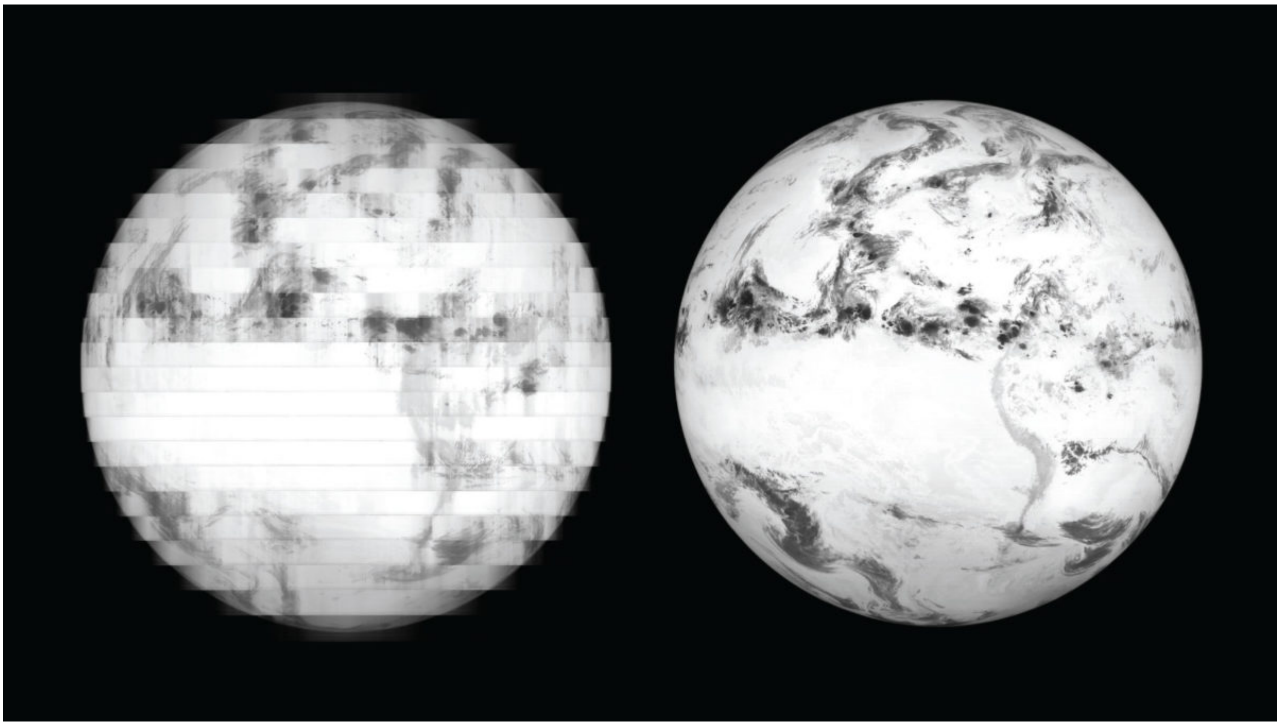


Figure 8. Degraded Image from Elevated Detector Temperatures (left)
and after Mitigations in Place (right) (Photo courtesy of NOAA)

3 GOES-R MAGNETOMETER PERFORMANCE

This section describes the Magnetometer (MAG) performance issue first identified on GOES-16, and the improved calibration designed to help maximize science return on the following vehicles in the GOES-R series. Subsequent steps included modifications to the instrument on GOES-17, and improved in-flight calibration procedures that utilized the entire torque and momentum operating envelope of the spacecraft.

3.1 Overview of GOES-16 Magnetometer Performance Anomaly

The GOES-16 Magnetometer (MAG) instrument performance was less than expected, and efforts were undertaken by the program to improve the performance for GOES-17. The observed MAG performance produced in-flight errors routinely exceeding the 1.7 nT accuracy requirement. As part of the MAG performance investigation, a key element to improving the overall MAG performance focused upon improving the calibration procedure. Unlike the GOES-16 MAG calibration procedure, the new calibration procedure developed utilizes the entire GOES-R torque and momentum performance envelope. Additional time was also allocated to performing the longer calibration maneuvers. This calibration was executed twice on GOES-17, with the residual bias error less than 0.75 nT for both the inboard and the outboard magnetometers. Although the GOES-18 spacecraft incorporated a different MAG instrument, this same calibration was successfully executed on GOES-18 during the post-launch test campaign.

Magnetometer performance is maintained by estimating the magnetometer zero offset bias drift and magnetometer sensor reference frame alignment error periodically while on-orbit. This estimation requires a spacecraft maneuver to provide the observability needed by the calibration algorithm. It also requires a quiet Earth magnetic field that does not fluctuate significantly over the duration of the maneuver. Based upon performance trending observations in flight, annual calibrations using the calibration outlined here may be needed in order to provide accurate instrument measurements. Any additional calibration maneuvers will be planned by the ground operations team as required.

3.2 Magnetometer Anomaly GN&C Accommodations

The improved calibration procedure increases the spacecraft angular rate of rotation (up to 0.85 deg/s) and uses larger rotation angles (1080 deg) compared to the original MAG calibration maneuvers. Three revolutions are performed first about the deployed MAG boom axis, and then three revolutions are performed about an axis orthogonal to the MAG boom axis. The vehicle rate profile for the resulting 6-revolution calibration is shown in Figure 9. A nominal timeline of 82 minutes is needed to perform the 6-revolution spacecraft maneuver, including the setup and recovery slews.

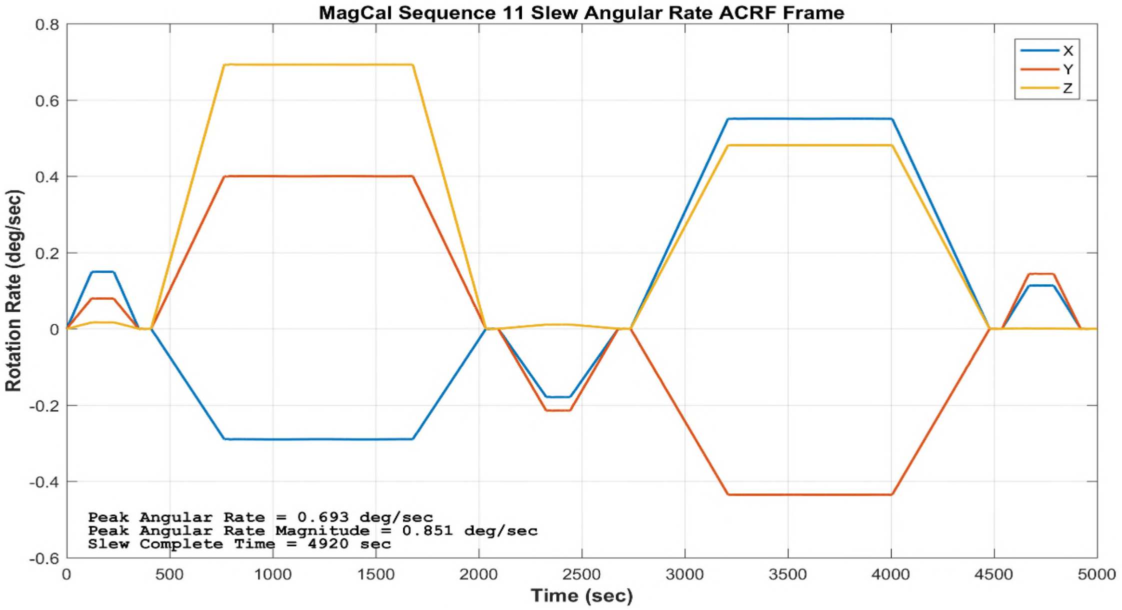


Figure 9. Spacecraft Body-Frame Rotation Rates during 6-revolution MAG Calibration

To maintain communications, the forward hemispherical antenna must be kept within view of the ground station. For the profile above, the maximum antenna offpoint from the NASA/Wallops ground facility is 59 deg. This ensures adequate link margin for telemetry downlink during the entire calibration.

As presented in Table 1, the torque and momentum capabilities of the spacecraft are not symmetrical. In body coordinates the spacecraft is limited to 233 Nms momentum and 1.27 Nm torque in the X-Z plane. But, in the worst-case direction, those numbers drop to 181 Nms and 0.99 Nm. These constraints govern how the maneuver sequence can be executed and the maximum rate of the vehicle during the calibration. The rate profile shown in Figure 9 satisfies these constraints. The flight results of the reaction wheel speeds (momentum) and torques are shown in Figures 10 and 11, respectively. As seen in the plots, ~85% of the reaction wheel momentum capability and ~92% of the reaction wheel torque capability were utilized during the GOES-17 MAG calibration maneuvers. If the limits had been exceeded in either case, a Safe Mode entry likely would have occurred.

The algorithms used to calculate instrument biases and misalignments from on-orbit data are executed offline and are not part of the routine science data product set. The calibration algorithms use batch least squares estimation techniques to calculate both bias and misalignment terms from the data collected during the calibration maneuvers. Two techniques were developed, one by Lockheed Martin and one by NASA/GSFC. Calibration results using both of these techniques are presented in the next section.

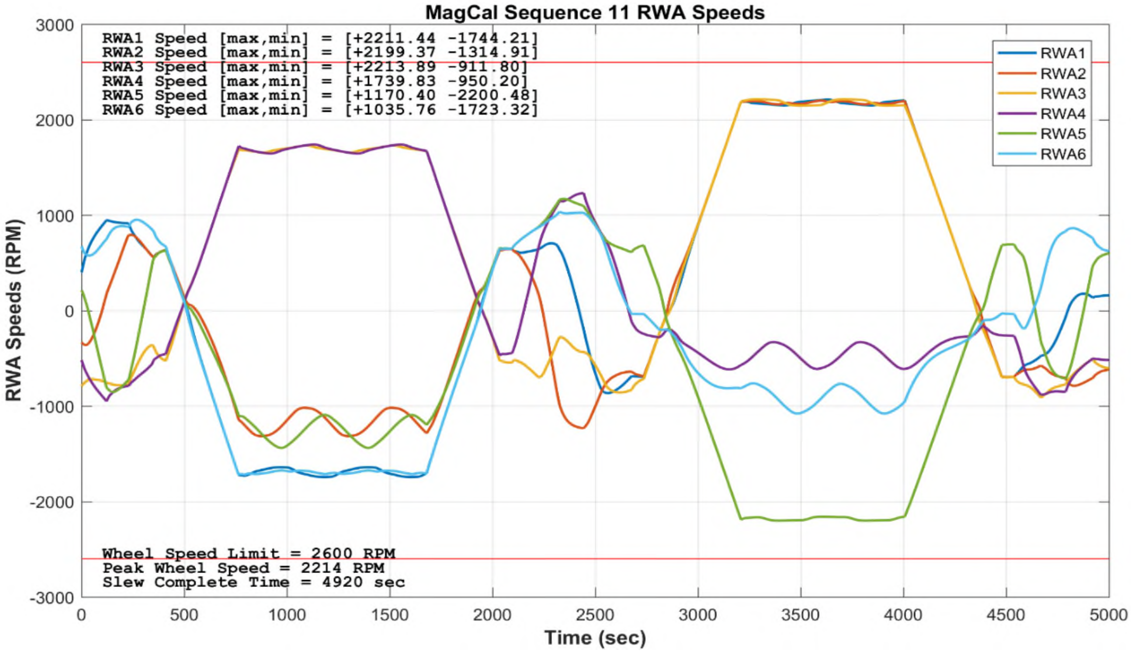


Figure 10. GOES-17 Reaction Wheel Speeds during 6-revolution MAG Calibration

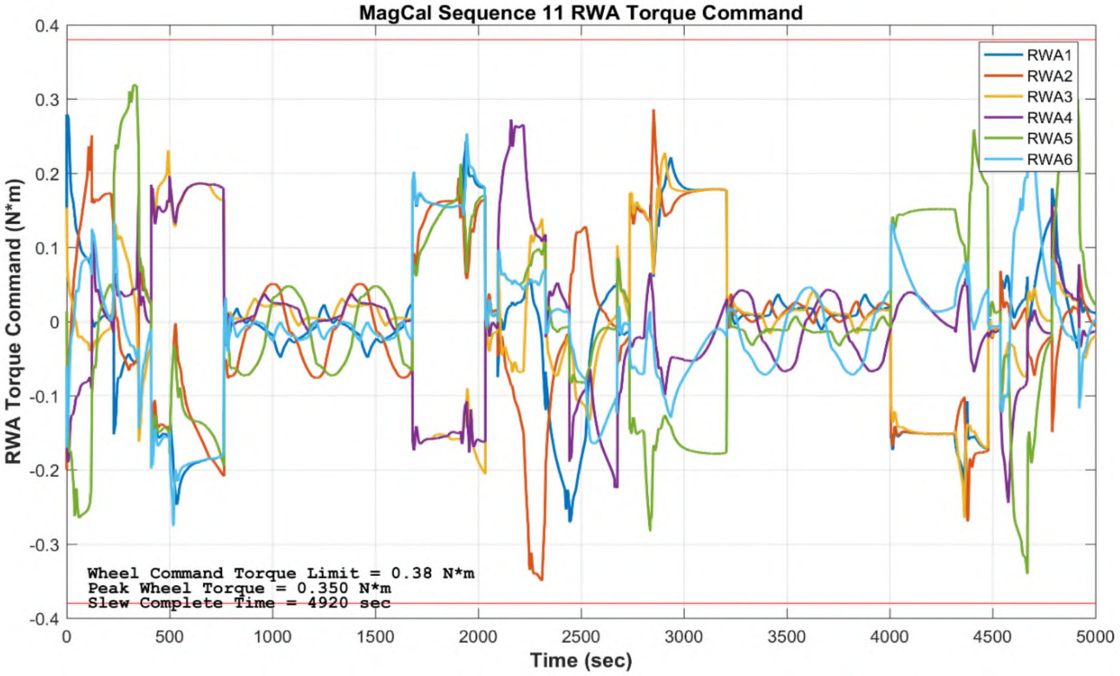


Figure 11. GOES-17 Reaction Wheel Torques during 6-revolution MAG Calibration

3.3 Magnetometer Calibration Results from Modified Procedure

From the 6-revolution calibration discussed above, revolutions 1, 2, and 3 provide full observability of the instrument X/Y axes, and revolutions 4, 5, and 6 provide full observability in the Z axis. As mentioned above, the program developed two separate techniques for calibrating the MAG instrument. Whereas the Lockheed Martin approach assumes a static magnetic field over a relatively short interval, the NASA/GSFC approach estimates the variations in the Earth’s magnetic field over the calibration time period. This allows more data to be used in the NASA/GSFC the MAG instrument calibration method. Alternatively, the Lockheed Martin method uses the X/Y results from the first three revolutions and uses the Z results from the last three revolutions as the “best” data set.

Figures 12 through 14 present the GOES-17 Out-Board (OB) magnetometer and In-Board (IB) magnetometer calibration results for the X, Y, and Z axes, respectively. The responses are shown using the pre-launch biases, NASA/GSFC computed biases and misalignments, and Lockheed Martin computed biases. Review of the plots shows that the pre-launch biases had significant offsets in the X and Y directions, although the pre-launch bias estimate in the Z direction had a much smaller error. The Lockheed Martin and NASA/GSFC methods both provide acceptable results, effectively removing the observed bias errors in the X and Y directions. Following the calibration, the 1.7 nT requirement is easily met on all three axes, with the residual error <0.75 nT. Based upon the success of the calibration, the 6-revolution maneuver has now been baselined for all MAG instrument shipsets.

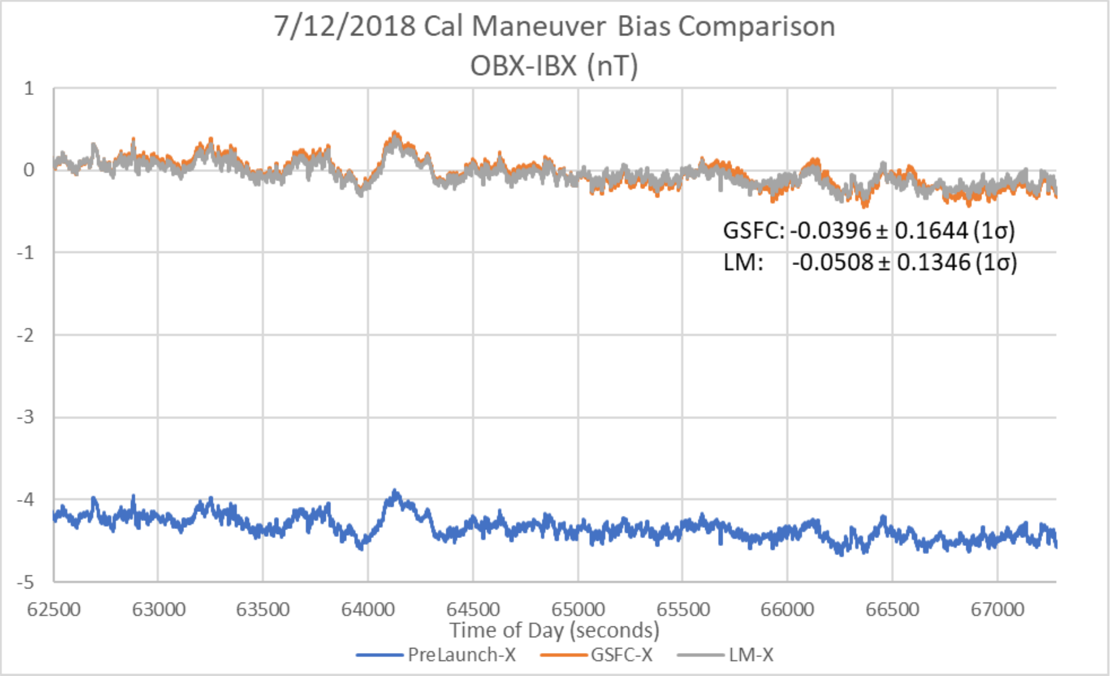


Figure 12. GOES-17 X-axis Outboard-Inboard Results for 6-revolution MAG Calibration

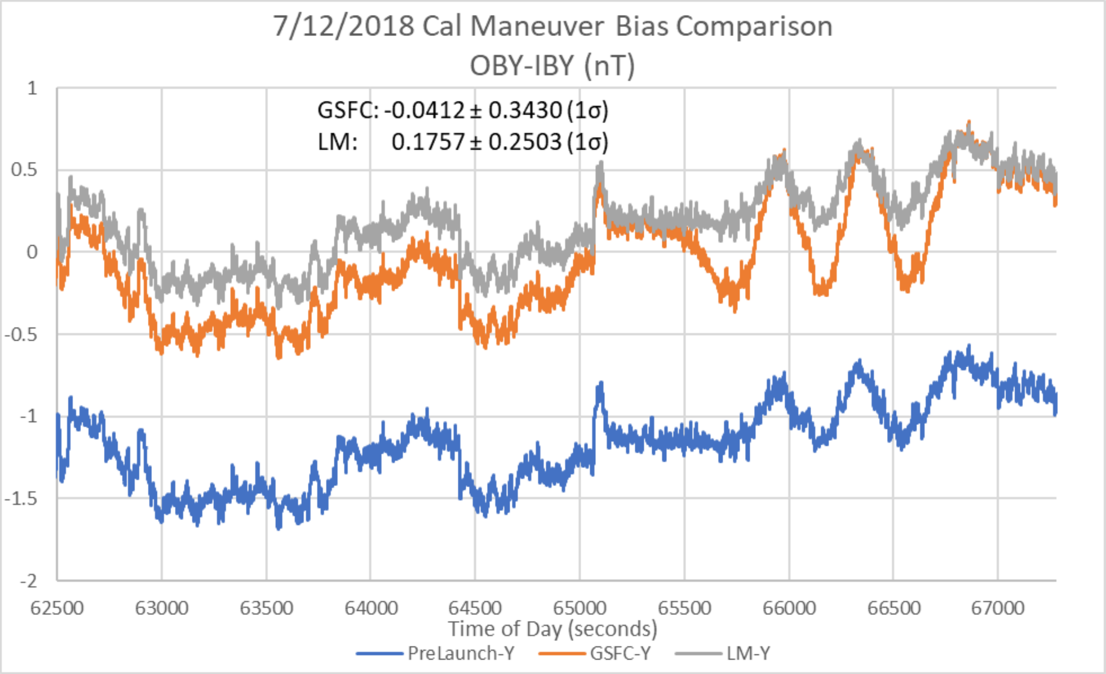


Figure 13. GOES-17 Y-axis Outboard-Inboard Results for 6-revolution MAG Calibration

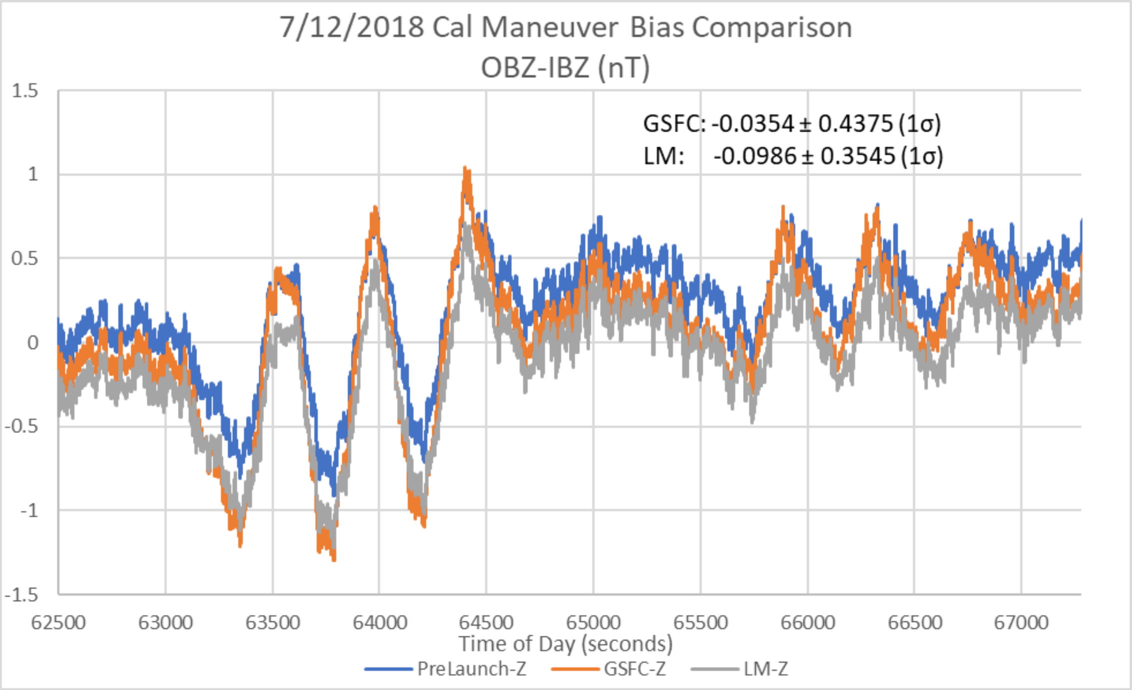


Figure 14. GOES-17 Z-axis Outboard-Inboard Results for 6-revolution MAG Calibration

4 CONCLUSION

The GOES-R GN&C architecture includes significant design margin and flexibility to modify the operational plan post-launch. GOES-17 has effectively utilized the GN&C design robustness to restore the ABI instrument science return to an acceptable level of performance, and to enable specification-compliant MAG instrument accuracy. The embedded robustness includes a high torque, high momentum capacity reaction wheel configuration incorporating a high level of redundancy with 6 reaction wheels. The Linf controller implementation allows this configuration to be exploited to its fullest potential, which was successfully used in developing the instrument calibrations discussed in this paper. Finally, the margin included in the jitter performance allows the dual cryocooler option to be used in flight, even though it was not considered an operational configuration during the design and development of GOES-R. The robustness included in the architecture provided effective options for the GOES-17 Mission Operations team to address off-nominal performance issues observed in flight.

5 ACKNOWLEDGEMENTS

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