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GOES-R SPACECRAFT VERIFICATION AND VALIDATION COMPARED WITH FLIGHT RESULTS

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The Geostationary Operational Environmental Satellite, R-Series (GOES-R) represents a dramatic improvement in GEO weather observation capabilities over the previous generation.[1] To provide these new capabilities, GOES-R incorporates a number of new technologies flying for the first time. As with any new spacecraft design, extensive ground testing was performed to validate the vehicle performance. In this paper, we present several successes and several lessons-learned from the GOES-R verification and validation (V&V) efforts. Included are the Dynamic Interaction Test (DIT) results for jitter assessment, and comparison to flight results. Also included are the effects of thermally-induced alignment perturbations, along with post-launch mitigations. Finally, we discuss unexpected GOES-17 gyro performance, which caused a Safe Mode entry shortly after launch. V&V mitigations are presented, which will be used for the next two GOES-R vehicles.

INTRODUCTION

GOES-16 and GOES-17 represent the first two spacecraft in the GOES-R series. They were launched in November 2016 and March 2017, respectively, and have proven highly successful in flight.[2] The overall GOES-R spacecraft configuration is shown in Figure 1, which includes both Earth-observing and Sun-observing instruments. The GOES-R V&V program was developed to flush out issues with the design, and to identify problems with individual vehicle builds. In this paper, we explore several aspects of the GOES-R V&V program, and the corresponding lessons-learned from flight data. As with any new design, things were learned following launch.

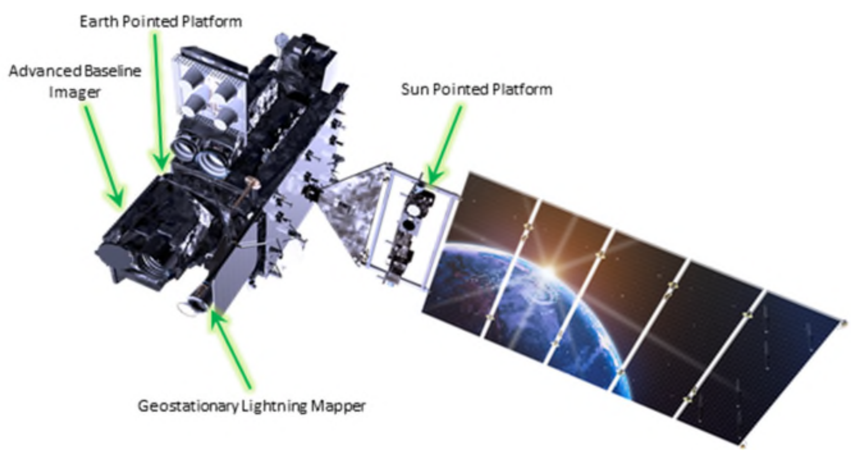

Figure 1. GOES-R Spacecraft in Operational Configuration.

Some aspects of the GOES-R design were recognized to be extremely challenging, and significant effort was expended pre-launch to prove the design would work as intended. The GOES-R instruments are sensitive to disturbances over a broad spectral range,[1,2,3,4] so significant V&V efforts were needed to prove the bus would provide adequate pointing and pointing stability. To predict jitter response, GOES-R developed a high-fidelity simulation with modal content up to 600 Hz. The DIT represents a specialized test developed to measure the jitter response during vehicle Integration and Test (I&T). In this paper, the analysis and DIT results are compared to flight observations for both GOES-16 and GOES-17. Six onboard Engineering Diagnostic Accelerometers (EDAs), seismic accelerometers sampled at ~2 kHz, allow direct comparisons.

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Several unexpected thermal-control sensitivities were observed in flight, including small alignment perturbations between the Inertial Measurement Unit (IMU), the star tracker, and the earth-observing instruments.[2] Additionally, the GPS Receiver (GPSR) accuracy was found to be thermally sensitive during certain operations. The capability of ground testing to measure these types of thermally-induced perturbations is limited, but as presented here, insight can be gained through specially configured tests. Thermal mitigations were put in place for GOES-17 based upon the results from GOES-16, which have improved the temperature sensing and thermal control capability for GN&C components.

On GOES-17, an unplanned Safe Hold Mode (SHM) entry occurred due to unexpectedly large gyro biases on 2 of the 4 gyros. These gyro biases were much larger than those observed on GOES-16. They were caused in part by the extended time between production of the IMU and GOES-17 launch. I&T signal to noise limitations make accurate gyro-bias measurements difficult at the vehicle level, but a relatively simple test has been developed to assess the gyro bias performance before launch. As presented here, this test has been successfully demonstrated on GOES-T, currently in production.

GOES-R JITTER VERIFICATION AND VALIDATION

Jitter requirements for the GOES-R nadir-pointed instruments have been cast in terms of linear translational accelerations and shock response spectra (SRS) at the instrument interfaces. The instruments are designed to meet their performance requirements in the presences of the higher General Interface Requirements Document (GIRD)[3] levels, while the spacecraft is designed to produce disturbances no greater than the lower Payload Resource Allocation Document (PRAD)[4] levels. The Government holds the difference between the two as unallocated reserve.

The requirements cover a broad frequency range up to 512 Hz. This drives the Earth-Pointed Platform (EPP) to be a stiff design, with passive isolation from the spacecraft bus.[5,6] To reduce the risk of reaction wheel (RW) disturbances impacting jitter performance, a secondary passive isolation system was incorporated under each of the six RWs, tuned to provide attenuation at frequencies >50 Hz.[5,7] Three significant V&V efforts are discussed: 1) the analysis used to show requirement compliance, 2) ground-based jitter validation tests conducted to reduce risk, and 3) in-flight jitter performance validation results.

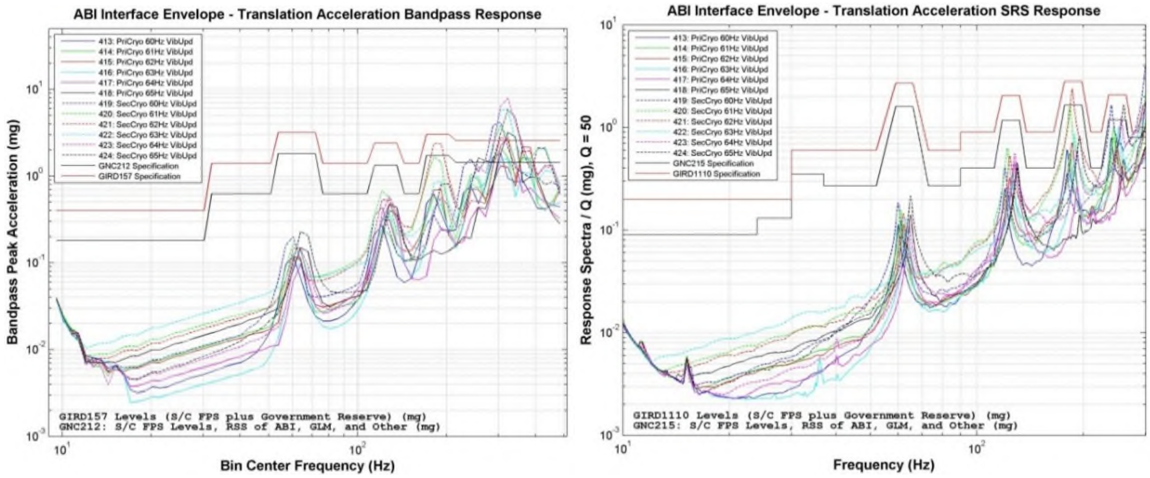
Jitter Analysis Approach

Jitter requirements were verified using a closed-loop GN&C high-fidelity jitter simulation with spacecraft dynamic models having frequency content up to 600 Hz.[1] The jitter simulation includes models of the spacecraft bus, appendages, EPP isolation, RWs, RW isolation, and instruments. The structural models are derived from the vehicle finite element model (FEM), but only the modes up to 600 Hz are retained. The structural damping is conservatively modeled, with the damping set to be 0.2% for modes less than or equal to 50 Hz, and 0.4% for modes greater than 50 Hz. To accurately capture the modal responses, the simulation is integrated at 8 kHz with key outputs recorded at 2 kHz.

The jitter simulation includes extensive modeling of disturbance sources. The simulation incorporates high fidelity models of the RW (motor ripple, static and dynamic imbalance, bearing eccentricity, and induced vibration), gimbal motors with harmonic drive disturbances, fuel and oxidizer slosh, instrument scan mirrors, and instrument cryocoolers.

Cryocoolers embedded in the Advanced Baseline Imager (ABI) dominate the jitter response. Special consideration was paid to the accurate modeling of the cryocooler disturbances. The cryocoolers each contain a compressor (integral unit) and a remote unit which produce 3-axis disturbance forces. These disturbances are modeled using a Fourier series expansion of the first eight harmonics per axis. The minimum operating frequency of each cryocooler is 60 Hz, so the first eight harmonics are captured in the jitter requirement set, which ranges up to 512 Hz. In the simulation, every harmonic for each axis starts with phasing set by a random-number seed, allowing repeatable behavior from run to run. The ABI supplier provided magnitudes of the harmonics for each axis. The simulation applies cryocooler disturbances at the FEM nodes for the cryocooler, and responses were tuned to match ground test data from ABI instrument testing.

Figure 2 shows envelope plots for responses from 15 different simulations. The responses include single cryocoolers running at different drive frequencies. The cryocooler drive frequency and its harmonics clearly show up as spikes in both the acceleration bandpass and the SRS responses. The ABI interface acceleration response shows compliance with the GIRD specification at all frequencies except ~310 Hz. The SRS response limit is met at all frequencies. The GIRD also includes separate jitter requirements for the other earth-observing instrument, the Geostationary Lightning Mapper (GLM). Although not presented here, all jitter requirements were met for the GLM interface.



a) Linear translation acceleration limits. *b) Linear translation SRS limits.*

Figure 2. Modeled ABI Mounting Interface Accelerations with Cryocooler Enabled.

To reduce the risk of possible exceedances in the interface acceleration requirements, the Flight Project developed line-of-sight (LOS) guidelines for both the ABI and GLM instruments. These guidelines represent a possible alternative specification for allowable jitter. Evaluation of the LOS performance is only possible with a high-fidelity, integrated structural model of the instruments and spacecraft designs, including optical degrees-of-freedom within the instruments. Enhanced structural models of the instruments were made available for this analysis and incorporated into the high-fidelity jitter simulation. Results of the LOS assessment for various cryocooler operating frequencies are shown in Table 1. The ABI LOS is shown for both East-West and North-South directions, whereas the GLM LOS is shown as a radial error. The GLM LOS guidelines are met with large margins for any cryocooler operating frequency. However, ABI LOS guidelines are not met for one of the six cryocooler frequencies shown. The North-South direction appears to be more sensitive than the East-West direction, although the LOS guidelines are also somewhat looser in the East-West direction.

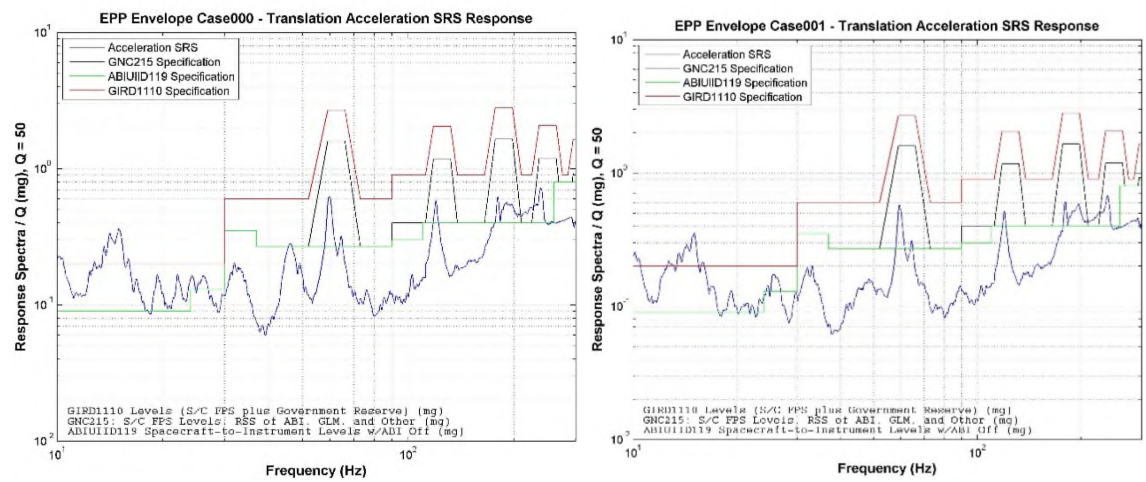
Table 1. ABI and GLM LOS Jitter Simulation Results.

ABI Cryocooler State	Primary Cryo Freq (Hz)	Secondary Cryo Freq (Hz)	SA & Mag Boom Thermal Snap	RW Isolation Temp (°C)	RW IV Dist. Magnitude (σ)	ABI LOS Jitter (micro-radians)								GLM LOS Jitter (micro-radians)			
						North-South				East-West				Boresight			
						3-sigma	Margin	3-sigma Limit	Peak	3-sigma	Margin	3-sigma Limit	Peak	3-sigma	Peak	Margin	Peak Limit
Off	-	-	On	20	0.0	0.376	74%	1.46	0.591	0.376	80%	1.89	0.618	0.061	0.097	84%	
VibeUpdate	60	-	On	20	0.0	1.346	12%		2.231	1.312	38%		2.174	0.136	0.242	60%	
VibeUpdate	61	-	On	20	0.0	2.080	-36%		3.236	1.233	41%		2.078	0.134	0.243	60%	
VibeUpdate	62	-	On	20	0.0	1.426	7%		2.519	1.399	33%		2.083	0.129	0.223	63%	
VibeUpdate	63	-	On	20	0.0	1.469	4%		2.423	1.432	32%		2.287	0.129	0.235	61%	
VibeUpdate	64	-	On	20	0.0	1.275	17%		2.101	1.133	46%		1.921	0.128	0.237	61%	
VibeUpdate	65	-	On	20	0.0	1.060	31%		1.788	1.051	50%		1.908	0.150	0.272	55%	

Ground-Based Jitter Validation

The analysis results above imply a sensitivity of the ABI LOS performance to cryocooler operating frequency. A small change in operating frequency could significantly impact LOS performance. To assess this and to validate the modeling, two ground-based jitter tests were run at the spacecraft level: 1) a measurement of ABI cryocooler disturbances exported during thermal vacuum testing, and 2) a DIT.

EDA data (six onboard seismic accelerometers to assess jitter in flight) were collected during portions of the GOES-R spacecraft-level thermal vacuum testing. Data were collected over 10-minute periods at the default rate of 2048 Hz. The ABI primary cryocooler was operated at a constant frequency for each collection interval, and data were collected for frequencies between 60 Hz and 65 Hz in 1-Hz increments. The test was repeated using the redundant cryocooler. The SRS responses are shown in Figure 3 for the 60-Hz cryocooler case. Below ~50 Hz the response is dominated by facility-induced noise, but at higher frequencies the fundamental cryocooler disturbance and harmonics are readily apparent. The same test was performed during GOES-S thermal vacuum with similar results. Because of conservative modeling assumptions, it is not surprising that this test demonstrated the jitter analysis to be conservative in the 200-300 Hz range. The test proved to be a good indicator that each spacecraft was assembled correctly without unexpected responses.



a) GOES-R EDA SRS response data. *b) GOES-S EDA SRS response data.*

Figure 3. Disturbance Measurements with the ABI Primary Cryocooler Operating at 60 Hz.

GOES-R system-level testing also included a specific test designed to measure structural dynamic responses due to instrument and satellite disturbance sources. The DIT results were used to validate the dynamic models of the satellite. Figure 4 illustrates how the EPP was offloaded, and identifies the flight and non-flight sensors available. Because of confidence in the analysis and results of component-level testing, the scope of the DIT was reduced from the original plan. Schedule concerns also prevented the test from being performed in the preferred facility, so the DIT was performed in the noisier high-bay facility used for most of I&T. The reduced-scope DIT focused on ABI disturbance sources only (cryocooler and scan mirror motion).

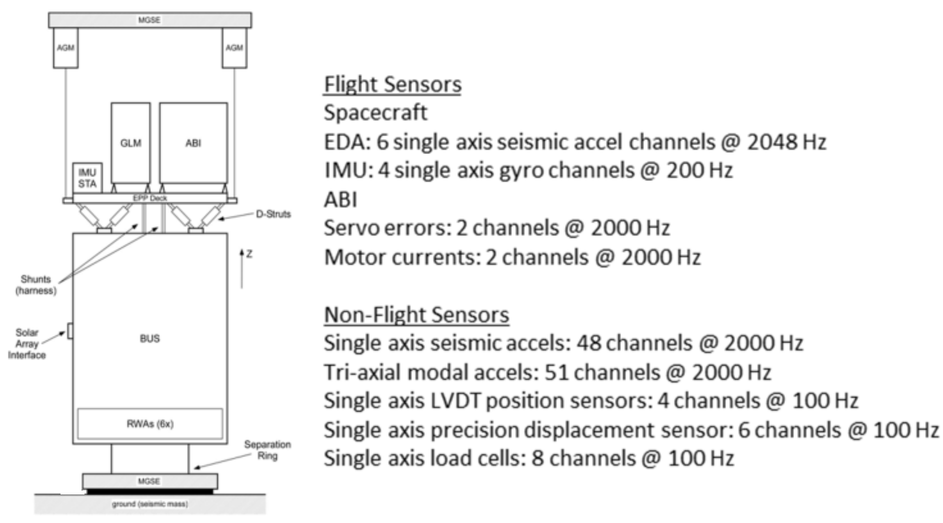
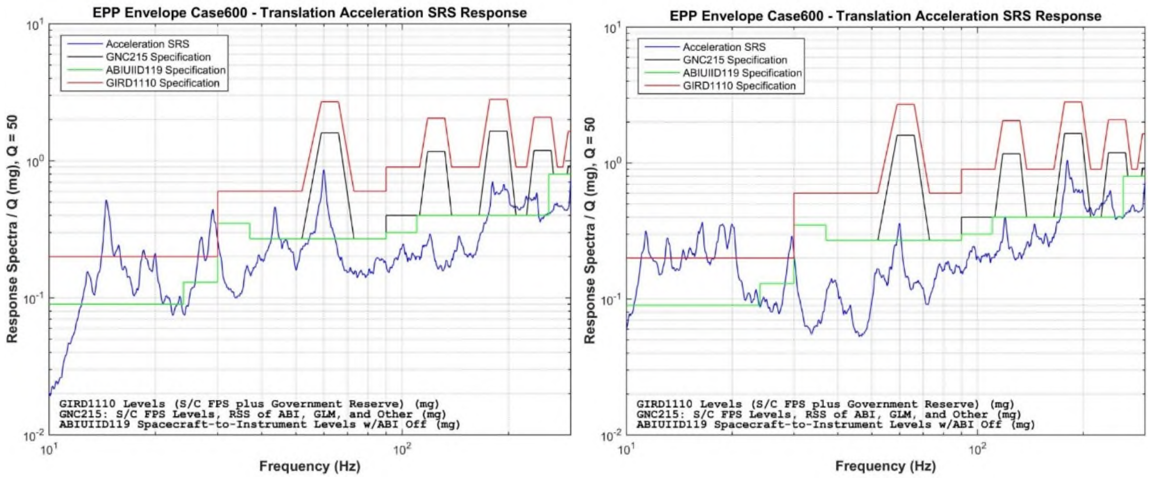


Figure 4. DIT Test Configuration with Flight and Non-Flight Sensor Data Identified.

Typical ABI interface acceleration SRS results are shown in Figure 5 with the EPP stowed and deployed.[5] No GIRD exceedances are seen above 20 Hz. The exceedances below 20 Hz were facility related, as evidenced by background accelerometer noise measurements. The results demonstrated significant design margin, allowing the DIT to be designated a “qualification” test—DIT testing on subsequent vehicles could be eliminated so long as the measured ABI cryocooler disturbances stayed in-family.



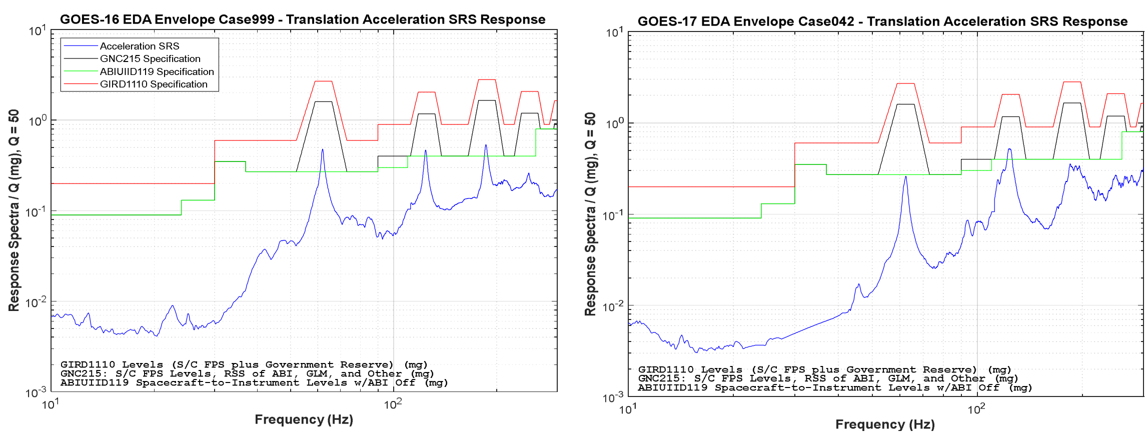
a) EPP stowed. *b) EPP deployed.*

Figure 5. DIT Results Showing EDA Enveloped SRS Response with Cryocooler Enabled @ 60 Hz.

In-flight Jitter Validation

Following launch, GOES-16 and GOES-17 were subjected to months of extensive testing prior to being put into operational service. EDA data were used to characterize the disturbance environment at the ABI and GLM interfaces. A routine, stressing scenario includes back-to-back momentum adjust (MA) and station-keeping (SK) maneuvers, where the RWs rapidly slew between positive and negative operating speeds. Both low-thrust REA's and arcjets are used during these maneuvers, exciting the vehicle structural modes and the fuel and oxidizer slosh modes. Throughout the maneuvers, all instruments remain fully operational in their nominal states, which includes the ABI scanning and the cryocooler operating.[8]

The SRS response envelopes from the EDA data are shown in Figure 6 for GOES-16 with only the ABI primary cryocooler operating and for GOES-17 with both the ABI primary and redundant cooler operating.[9] Despite the cryocooler operating differences, the responses are similar showing large margins relative to the GIRD requirements. The flight results demonstrate that the analysis techniques were conservative, as expected. The ground test and flight results show inclusion of both EPP and RW isolation may not have been absolutely necessary.



a) GOES-16 w/ primary cryocooler @ 62.1 Hz. *b) GOES-17 w/ primary cryocooler @ 62.6 Hz and redundant cryocooler @ 61.6 Hz.*

Figure 6. In-Flight Results Showing EDA Enveloped SRS Response During MA/SK Maneuver.

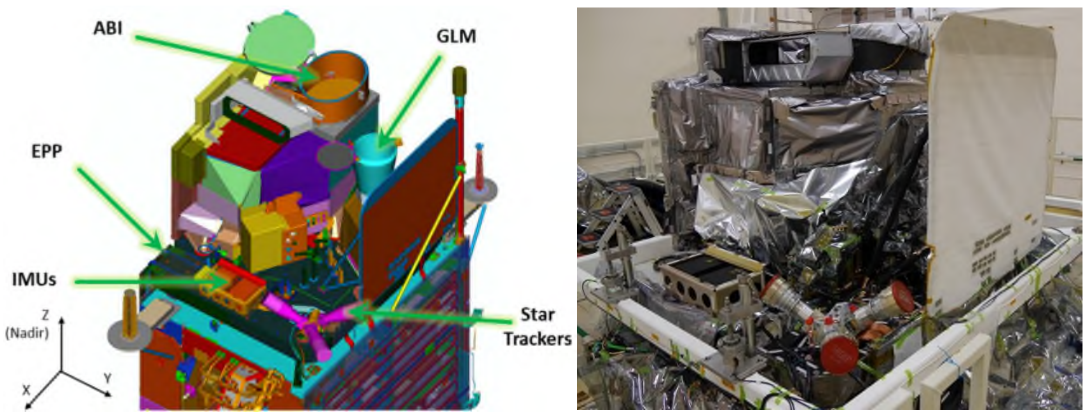
THERMAL ACCOMODATIONS FOR GN&C COMPONENTS

Shortly after GOES-16 launch, small periodic disturbances were observed in the instrument pointing. After some investigation, these disturbances were correlated with thermally-induced alignment changes on the star tracker and IMU. The disturbances were broken down into three categories: 1) IMU heater control induced alignment disturbances, 2) Star Tracker heater control induced alignment disturbances, and 3) Star Tracker vs. IMU diurnal alignment variation. This section presents the alignment disturbances observed in flight, the mitigations put in place, and a review of the pre-launch test data that might have uncovered issues pre-launch. Also discussed are the difficulties in validating these aspects of the thermal control design.

Although not initially noticed in the GOES-16 navigation performance, detailed reconstruction of the GOES-16 GPSR navigation performance showed unexpected degradation caused by baseplate temperature variations during certain operations. An interaction was discovered between the GPSR oscillator temperature sensitivity and the GPSR Kalman filter parameters for a specific operating mode, which primarily degraded radial position and radial velocity accuracy. This interaction is presented, along with mitigations put in place. Additional ground test results using a GPSR EDU are also discussed.

IMU and Star Tracker Thermal Control

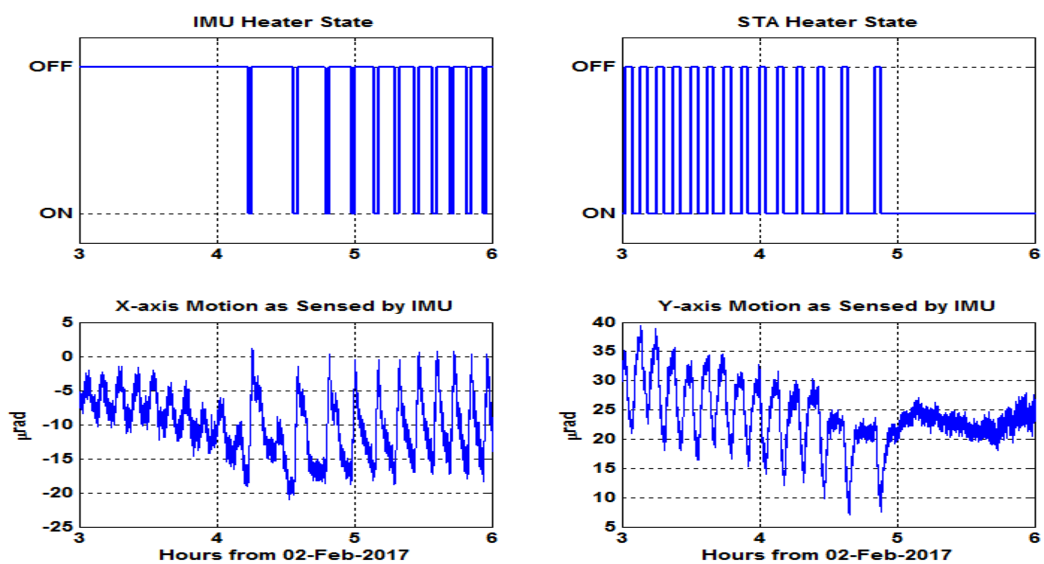
As reported previously, GOES-16 exhibited pointing perturbations shortly after launch.[1] Investigation showed correlation of these perturbations to thermal control of the IMUs and star trackers. The IMUs[10] and star trackers[11] are co-located with the earth-observing science instruments, as shown in Figure 7.



a) EPP Configuration for GOES-R. *b) GOES-16 EPP prior to final blanket installation.*

Figure 7. IMU and Star Tracker Configuration on the EPP.

Rate transients in the X-axis appeared to coincide with IMU heater cycles, and rate transients in both the X-axis and Y-axis appeared to coincide with star tracker heater cycles, although the star tracker heater Y-axis response was smaller. The rate transients caused a response by the attitude control software and a corresponding pointing disturbance. The attitude responses to heater cycling is shown in Figure 8.



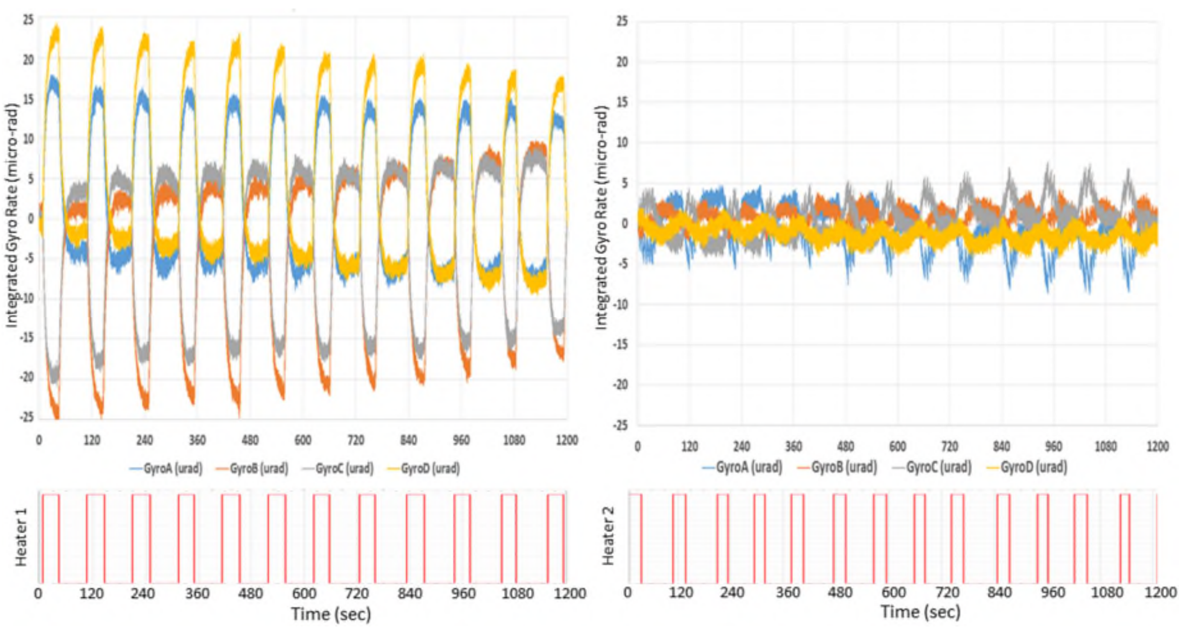
a) X-axis attitude response to IMU and star tracker heaters. *b) Y-axis attitude response to star tracker heaters.*

Figure 8. Pointing Perturbations Caused by IMU and Star Tracker Heater Control.

Ultimately, a software patch was implemented to improve the thermal control precision and decrease temperature variations. The patch increased both the temperature sensor sample rate and the heater command rate. The heater-on and heater-off setpoints were set to be the same temperature, effectively reducing the hysteresis to nearly zero. With these changes, the heater-induced transients have been reduced to less than 1-2 μrad, representing more than an order of magnitude improvement.

Once the correlation became clear from the GOES-16 flight data, the GOES-16 I&T data was reviewed to see if there was any evidence of these perturbations before launch. The spacecraft-level thermal vacuum testing includes the most flight-like operation of the various spacecraft heaters. Unfortunately, the nominal telemetry rates were too low, and the test facility was far too noisy for attitude variations of 10-20 μrad to be observed. Nominal flight operations for GOES-16/17 are somewhat unusual because high-rate IMU data is available at 100 Hz continuously. Typical I&T testing did not have the same telemetry available—this data was available only for short periods of time because of ground system limitations.

At the time of this GOES-16 investigation, the GOES-17 vehicle was available in I&T to perform some additional testing. A special test was developed to cycle the IMU and star tracker heaters while recording 200 Hz gyro data. Only IMU data were collected for this additional testing—there was no readily available method to measure star tracker line-of-sight variations. This test was performed in a much quieter facility than the spacecraft thermal vacuum test facility, allowing improved resolution. Representative results from this testing are shown in Figure 9. As can be seen in this figure, use of Heater 1 for thermal control produced alignment variations of ~30 μrad, much like those observed shortly after GOES-16 launch. Use of Heater 2 produced much smaller variations, barely above the resolution of the test. Clearly, Heater 2 is a better heater to use for controlling the baseplate temperature of IMU-1. If this test had been run prior to GOES-16 launch, including high-rate gyro data collection in a relatively quiet environment, the thermal control implementation could have been assessed for alignment perturbations. Nonetheless, the results of these tests, as well as the GOES-16 flight results, allowed thermal control improvements to be made on GOES-17.



a) IMU-1 gyro response to Heater 1 thermal control. *b) IMU-1 gyro response to Heater 2 thermal control.*

Figure 9. Integrated Rate Transients Caused by IMU Heater Control as Observed in Ground Test.

Star Tracker Diurnal Variation

To achieve the tight pointing and pointing stability requirements demanded by the GOES-R earth-observing instruments, the relative alignments of the IMU, star trackers, and the instruments needed to be tightly controlled. Alignment variations caused by diurnal temperature fluctuations was recognized as a potential issue during the design phase. As such, the thermal control design was intended to maintain the IMU and the star tracker baseplates at a constant temperature throughout the day, for every day of the year. Both the IMU and the star tracker thermal accommodations include relatively large radiators. That way, they can both be actively controlled with heaters. The short-term alignment perturbations caused by heaters was addressed in the previous section. However, a different thermal issue was also observed on GOES-16—during the winter months, the star trackers did not stay under active heater control throughout the day. During the portions of the day where the +Y side of the spacecraft was directly exposed to the Sun, the star tracker temperatures would rise dramatically. This is shown in Figure 10. The star tracker radiator was not able to keep the star trackers sufficiently cool for this sun-relative orientation. As seen in the figure, the predicted star tracker temperature at the baseplate was expected to be nearly flat at ~15 deg C. However, the star tracker temperature profile in flight showed a large diurnal excursion of more than 20 deg C over a period of ~10 hours. A corresponding perturbation to the spacecraft pointing of >100 μrad was also observed.

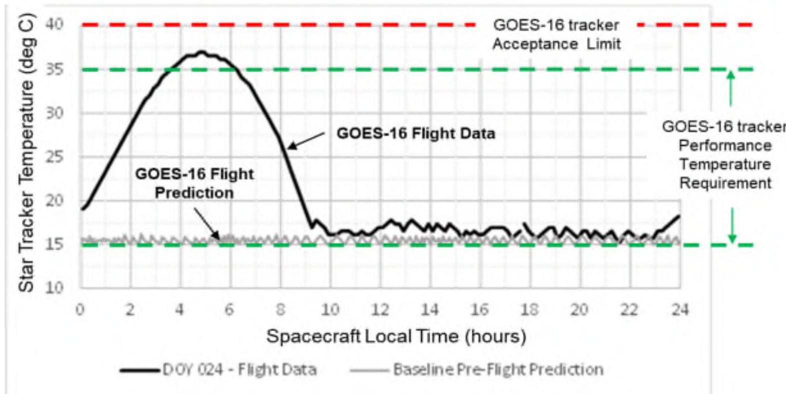


Figure 10. Star Tracker Diurnal Temperature Profile, Predicted vs. Observed.

For GOES-16, the capability to mitigate this effect are limited. Because of the slow sun-relative motion at GEO, the peak temperature is essentially at equilibrium. Only a change in spacecraft attitude can reduce the peak temperature, which would seriously disrupt instrument operations. However, the magnitude of the variation can be reduced by raising the heater setpoint from 15 deg C. By seasonally raising the set point to 30 deg C, the alignment and pointing perturbations have been reduced by >3X. This has provided acceptable pointing performance for the science instruments.

For GOES-17, modifications were made to the star tracker thermal accommodations, including increasing the size of the radiator and adding additional heaters. A comparison of the GOES-16 vs. GOES-17 performance is shown in Figure 11 for the same sun-relative geometry. As seen in the figure, the GOES-17 design modifications dramatically reduced the diurnal temperature variations. The corresponding star tracker diurnal alignment perturbations were reduced to negligible levels.

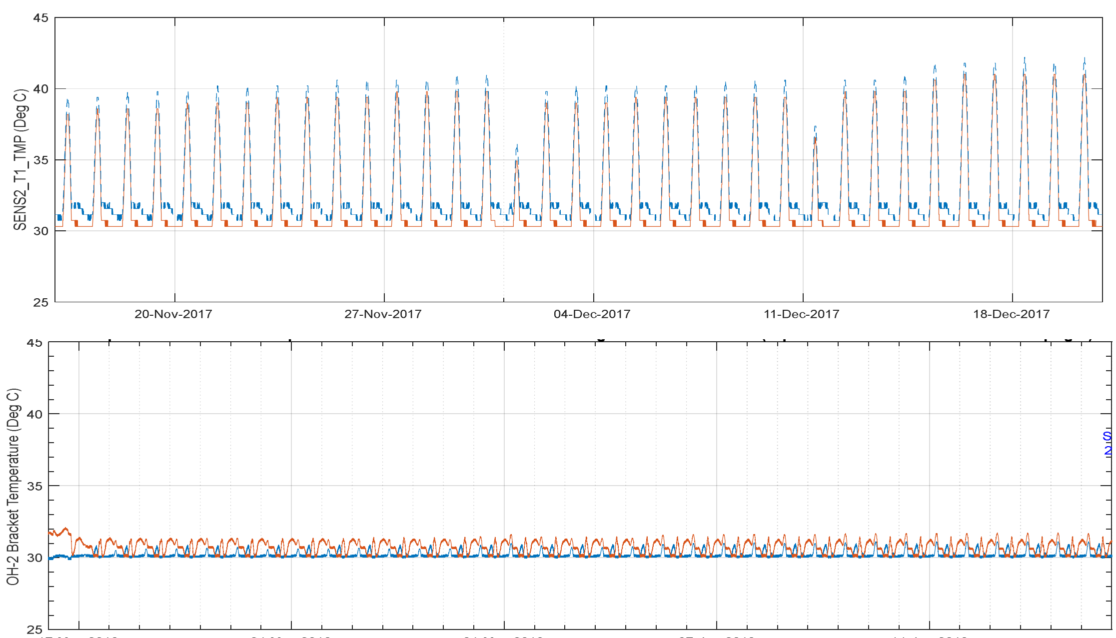


Figure 11. GOES-16 (top) & GOES-17 (bottom) Star Tracker Temperature for same Sun Geometry.

An investigation into the thermal model predictions revealed shortcomings in the model validation process, which used data from spacecraft thermal vacuum testing. Much of spacecraft thermal vacuum testing is focused upon thermal balance at stressing hot and cold conditions, and the GOES-R thermal models were correlated to these conditions. However, a solar exposure test was not performed for GOES-R, which may have uncovered the star tracker thermal control design deficiencies during ground testing. Solar testing is difficult for a spacecraft as large as GOES-R, especially if the test objective is to characterize the thermal response for all possible sun geometries. However, testing for sun exposure on the IMU and star tracker radiators could have provided very valuable information. Alignment perturbations could not have been readily measured, but that would not have been necessary. As GOES-17 flight data show, it would have been sufficient to demonstrate the IMU and star tracker baseplates could be maintained at constant temperatures.

GPSR Clock Drift Sensitivity to Thermal Control

The GPSR developed by the GOES-R program for use at GEO[12,13] uses an EMXO oscillator that is sensitive to temperature variations. The GPSR accurately compensates for thermally-induced clock drift variations during most operations. However, changes in the GPSR Kalman filter parameter settings can significantly degrade the clock drift compensation. Parameter changes are routinely made on GOES-R, as a different set of Kalman filter parameters is used during MA and SK maneuvers. This allows the GPSR solution to better track small orbital changes. However, the original "maneuver" parameter set implements "clock coasting," which causes a linear clock drift extrapolation when this parameter set is used. Because the oscillator temperature is not precisely controlled in flight, the resulting clock drift error can corrupt the radial velocity and radial position solutions during maneuvers. An example of this radial error during a GOES-17 SK maneuver is shown in Figure 12, where "truth" is provided by a ground reconstruction of the maneuver.

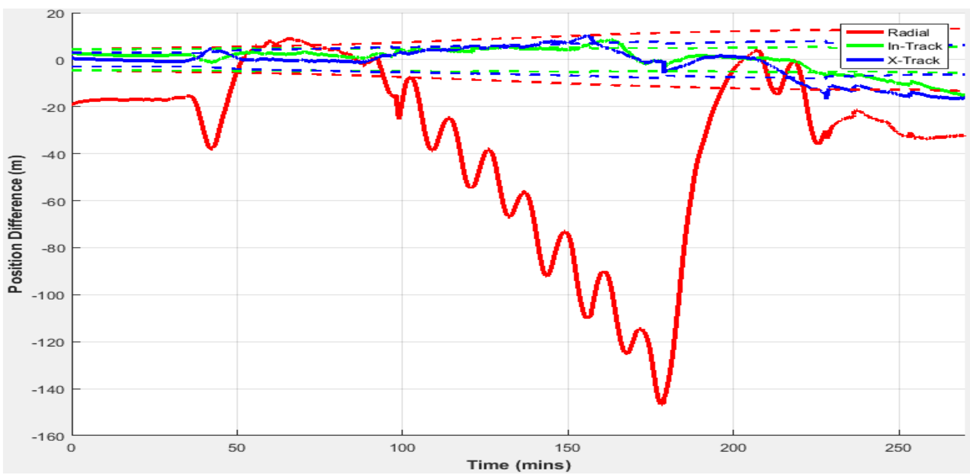


Figure 12. GOES-17 On-Orbit Thermal Conditions and Clock Drift.

In hindsight, there was an oversight in the GPSR verification—the GPSR performance for maneuvers was only tested at constant baseplate temperatures. In flight, the GPSR baseplate temperature may vary by several degrees from thermal control. The oscillator performance sensitivity to small temperature variations, and the resulting GPSR performance degradation when using the original Kalman filter maneuver parameter set, were not recognized prior to launch.

In flight, clock drift has been directly correlated with the oscillator temperature, as shown in Figure 13. There are three different maneuvers shown, where the original GPSR Kalman filter maneuver parameters were used during each maneuver. The top plot shows the temperature profile, and the lower plot shows a disagreement between GPSR-computed clock drift and a reconstructed clock drift during the three maneuvers. Outside of the maneuver periods, the GPSR computed clock drift error is dramatically smaller.

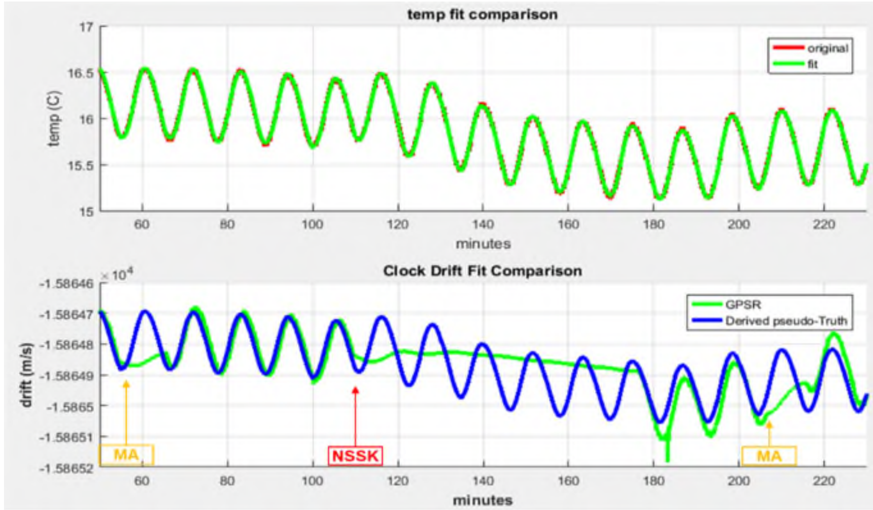


Figure 13. GOES-17 On-Orbit Thermal Conditions and Clock Drift.

A very simple heater control scheme was originally implemented for the large spacecraft panel where the GPSR is located. All 14 panel heaters were set to cycle on when any temperature sensor on that panel reached a parameterized set point. The heaters would remain on until all sensors were above a parameterized set point. This simple implementation resulted in the heaters cycling all the time, producing relatively large temperature ramp rates. Because of the clock drift issue discussed above, the resulting temperature oscillations caused GPSR navigation performance issues during maneuvers. An updated thermal control scheme was developed after GOES-17 launch, where the on and off commands for the 14 panel heaters were now staggered at various temperature set points. This resulted in reduced heater duty cycles, and smoother temperature profiles. Two different thermal control iterations were implemented with the second iteration providing dramatically improved thermal stability for the GPSR baseplate. The improved thermal control of the GPSR, along with the resulting improvements in clock drift stability, are shown in Figure 14.

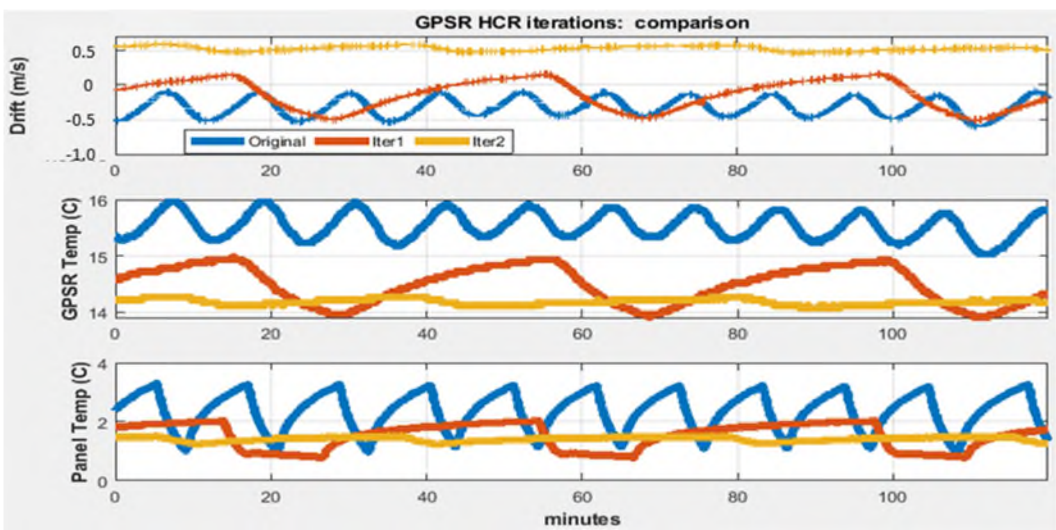


Figure 14. Temperature and Clock Drift Profiles for Thermal Control Iterations.

The GPSR performance during maneuvers was significantly improved with this updated thermal control scheme. Following the discovery of the GPSR oscillator thermal sensitivity, additional ground testing was undertaken to further improve GPSR performance during maneuvers by tuning the Kalman filter parameters. Testing of an EDU GPSR was performed while inducing flight-like thermal control variations. A temperature profile was loaded into the baseplate thermal controller, producing thermal profiles for the GPSR oscillator similar to worst-case profiles observed on-orbit. The GPSR Kalman filter parameters were iteratively tuned using flight-like MA and SK maneuver scenarios using this test setup. Modifications were made to the GPSR

Kalman filter maneuver parameters in the fall of 2018. Flight results from both GOES-16 and GOES-17 now demonstrate full compliance with navigation requirements during maneuvers.[14]

ATTITUDE ACQUISITION IMPACTS OF UNKNOWN GYRO BIAS

The GOES-17 launch represents the second of the GOES-R series. Several thermal control design modifications were made for GOES-17, as discussed above, as well as several minor software modifications. But otherwise, the vehicle was essentially the same as GOES-16. The ground V&V program went relatively smoothly, so no issues were expected following launch. Unfortunately, this was not the case. On March 1, 2018, the GOES-17 launch, separation, initial deployments, and sun acquisition all went smoothly. However, the initial attempt at attitude acquisition resulted in the primary IMU being marked "failed", which then triggered a Safe Mode entry and a swap to the secondary IMU. Attitude acquisition on the secondary IMU proceeded nominally. Telemetry rates were very low during attitude acquisition, so it was not readily apparent what caused the IMU swap and Safe Mode entry.

GOES-17 Safe Hold Mode Entry Analysis

The GOES-R attitude acquisition implements a 3-step process: 1) star acquisition with the star tracker, 2) reset of the gyro-propagated attitude to match the star tracker solution, and 3) start of the 6-state attitude determination Kalman filter.[15] Step (1) is initiated by the ground, and step (2) is completed automatically once the star tracker finds a solution. Step (3) is initiated by the ground once star tracker telemetry is assessed. Prior to GOES-17 launch, there was no time constraint in place between step (2) and step (3). For GOES-17, the ground team observed some unusual telemetry associated with the star tracker solutions following step (1), which was attributed to stray light. The ground allowed the star tracker telemetry to stabilize before commanding the Kalman filter to start running, which resulted in a delay of ~12 minutes. Upon starting the Kalman filter, the star tracker solutions immediately violated the filter's residual magnitude check, resulting in IMU-1 being marked "failed" shortly thereafter. The GOES-R fault management architecture[16] invokes Safe Mode for attitude determination problems, and swaps to the other IMU. Following Safe Mode entry, attitude knowledge was successfully acquired using IMU-2.

Telemetry during this period was very sparse due to the low downlink rates used during this phase of the mission. Based upon the data available, a reconstruction of events postulated two possible causes of the observed behavior: 1) a misalignment of the star trackers, which could produce a jump in the star solution when the 2nd optical head began tracking stars, and 2) and out-of-specification gyro bias. The timeline is shown in Figure 15. Only 3 data points of the residual bias were available from telemetry, so simulations of the attitude acquisition process were performed to fit the 3 data points. Other telemetry data were available at higher rates, such as the attitude quaternion and attitude rate data. As can be seen in the residual plot, the attitude change when the 2nd star tracker solution became available was noticeable but was small relative to the Kalman filter residual limit. The investigation was then focused upon the gyro bias behavior.

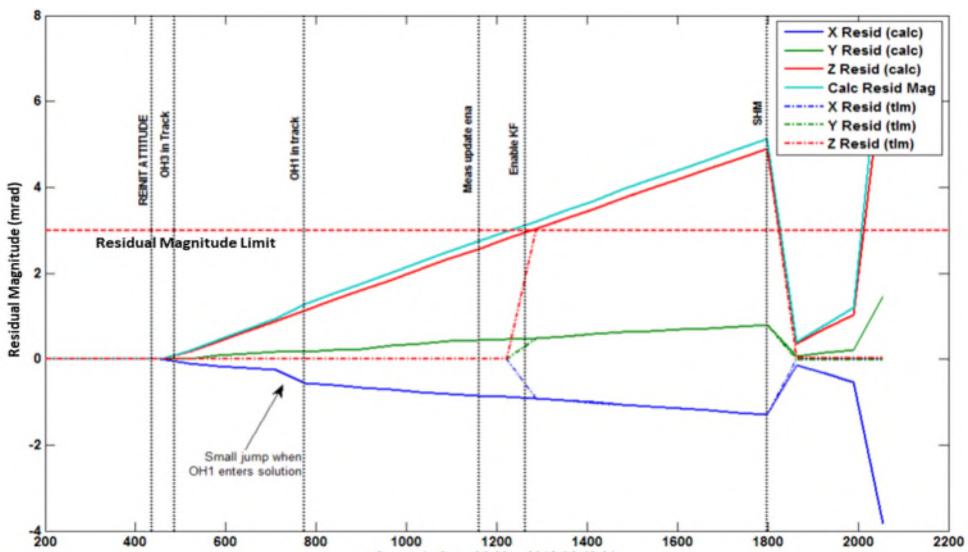


Figure 15. Star Tracker Measurement Residuals Computed from Telemetered Quaternions.

Only limited telemetry was available for each of the 4 gyros, but a reconstruction based upon star tracker quaternion data indicated elevated gyro bias on 2 of the 4 gyros. The reconstruction showed biases for Gyros B and D of less than 0.1 deg/hour, which is within expectations. But Gyros A and C had biases of 1.0 deg/hour and 0.7 deg/hour, respectively. These are much larger than expected and combined with the 13 min delay in starting the Kalman filter, are large enough to cause the observed behavior. If the delay had been shorter than ~10 min, no anomaly would have been observed.

Although fault management did not indicate any problems with IMU-1 other than the large biases, the program initiated activities to assess the health of the unit. Once GOES-17 instrument calibration activities were underway, swapping back to IMU-1 would have been very disruptive, and would have also involved some unquantified risk. The flight software architecture generally allows only a single IMU to be powered, but products were developed to power on IMU-1 while still using IMU-2 for attitude control. These products were designed to provide sufficient telemetry to assess IMU-1 component health, and to gather limited performance data. The results of this test are shown in Figure 16. As can be seen from the figure, the gyro A and gyro C biases are indeed elevated. The observed biases are 1.25 deg/hour and 0.85 deg/hour respectively, slightly higher than launch day. Diagnostic telemetry showed the unit to be healthy in all other respects.

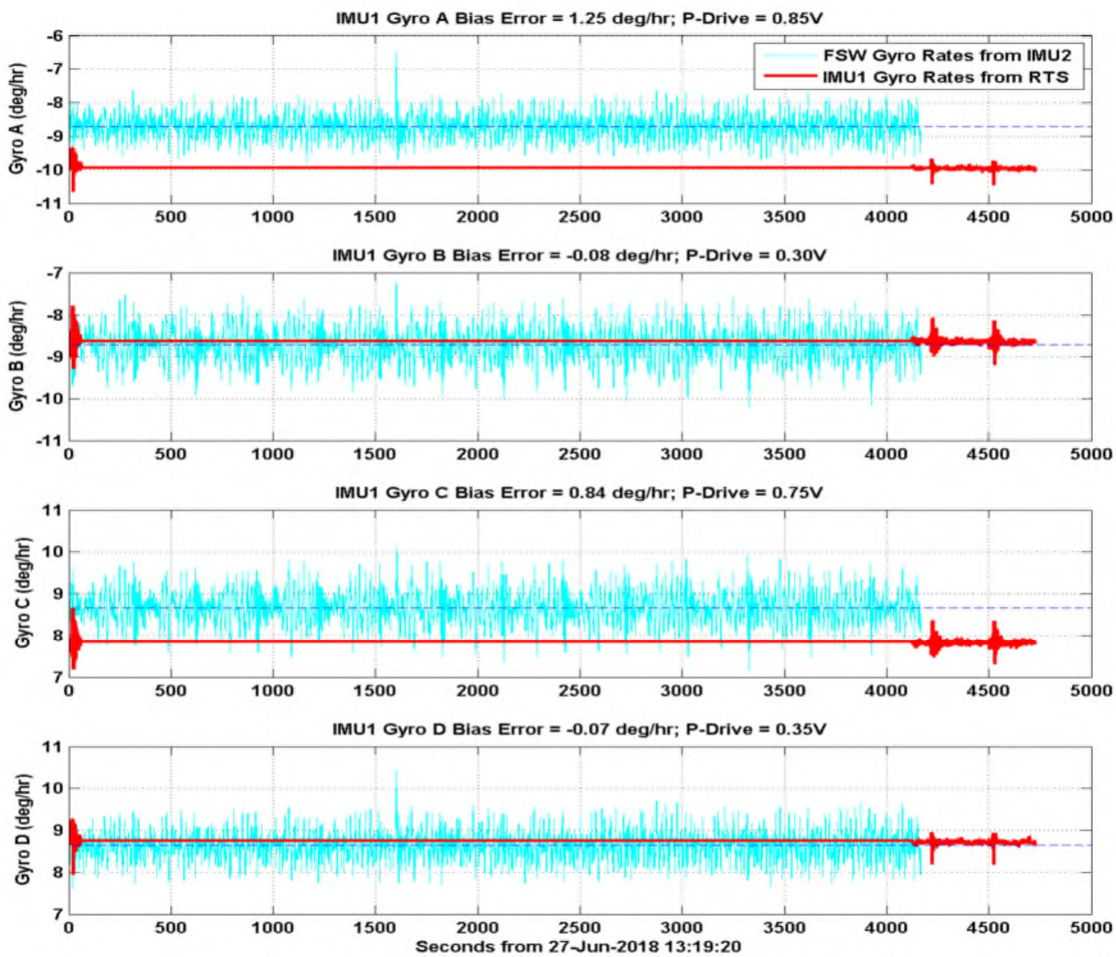


Figure 16. IMU-1 Gyro Bias Measurement from Simultaneous Operation of Both IMUs.

Vehicle-level Gyro Bias Testing in I&T

A review of the I&T data did not show any indications of anomalous performance for IMU-1. However, no I&T tests had been performed specifically to assess the gyro bias performance before launch. Following the unexpected gyro performance seen on GOES-17, the GOES-R program requested that additional IMU testing be performed at the vehicle level during I&T. This would allow compensation for any anomalous gyro bias behavior. A gyro bias estimation test has been developed and run on the GOES-T vehicle in I&T. IMU data has been collected in three different orientations on GOES-T. The orientations were chosen to maximize the difference in measured earth rate on each gyro between the orientations. The "home" orientation has the spacecraft X&Y axis aligned with the high bay walls and primarily serves as a reference for the other two orientations, however data was collected in the home orientation and used in the bias computation as well.

Expected or "truth" rates for each gyro were computed using alignment measurements relative to true north and down, along with the test facility latitude and longitude to project the earth rotation onto each gyro axis. The average rate per gyro was calculated over each 20-minute set of 200 Hz data. These true and measured rates are tabulated in Table 2 for the GOES-T IMU-2. The IMU-2 is shown here because it has one gyro with elevated bias discovered during acceptance testing. The larger bias of gyro C is easily discernible by differencing the expected and measured rates. A fit of this data to a first order polynomial is presented in Figure 17. The Gyro C bias error is similar in magnitude to the errors seen on the GOES-17 IMU-2 Gyros A and C. Even in a relatively noisy high-bay environment, the bias estimate resolution is very accurate, and could be used to update the bias estimate to within ~0.02 deg/hour. The scale factor estimates (SFEs) from this test are probably less useful than the bias estimates. SFEs measured during GOES-16 and GOES-17 on-orbit calibrations were roughly an order of magnitude smaller. Only a very large SFE would be discernable with this test methodology.

Table 2. GOES-T IMU-2 Expected and Measured Rates from Bias Characterization Test.

Gyro	Home Orientation		Orientation 1		Orientation 2	
	Truth	Meas	Truth	Meas	Truth	Meas
A	1.6236	1.6079	-1.3273	-1.3421	12.3915	12.3472
B	-3.1157	-3.1025	12.0635	12.0507	-0.9786	-0.9614
C	9.4055	10.2364	12.3699	13.2023	-1.3609	-0.4556
D	14.1634	14.0144	-1.0276	-1.1401	12.0469	11.9155

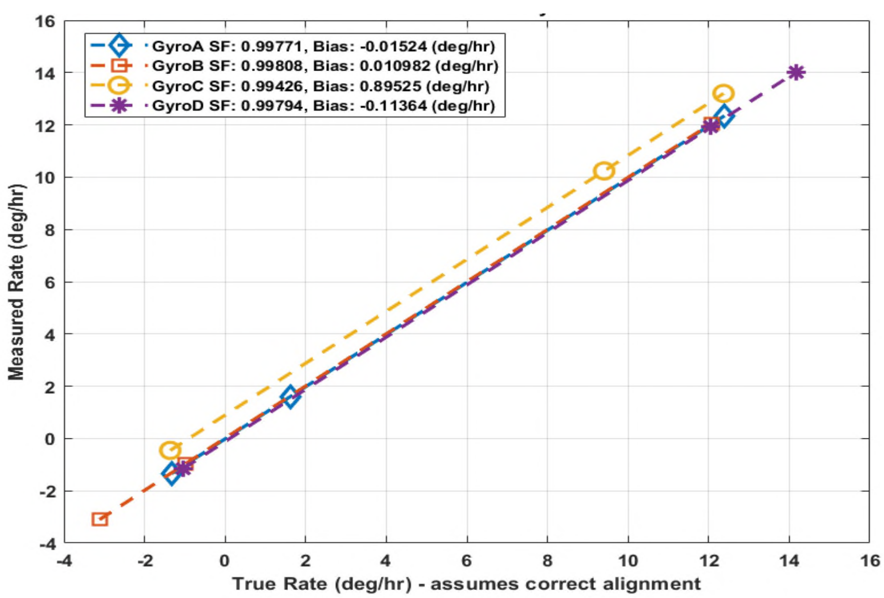


Figure 17. GOES-T IMU-2 Gyro Bias and Scale Factor Error Estimation from I&T Test Data.

CONCLUSION

As we have shown in this paper, an effective V&V program is vital for demanding spacecraft designs that push the performance envelope. Even with extensive V&V, some unexpected in-flight behavior will undoubtedly occur for a new design. Flight telemetry with sufficient sampling rate and resolution will allow insight into on-orbit behavior. A robust test capability will allow ground correlation of the flight observations. And, margin within the design will allow effective mitigation strategies to be implemented. Fortunately, the GOES-R program included all of these, allowing GOES-16 to implement effective mitigations in flight. The GOES-17 design modifications proved effective in mitigating the anomalies observed on GOES-16, but a different anomaly occurred requiring a new mitigation to be implemented.

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