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GOES-R DUAL ISOLATION

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The Geostationary Operational Environmental Satellite-R Series (GOES-R) is the first of the next generation geostationary weather satellites, scheduled for delivery in late 2015. GOES-R represents a quantum increase in Earth and solar weather observation capabilities, with 4 times the resolution, 5 times the observation rate, and 3 times the number of spectral bands for Earth observations. With the improved resolution, comes the instrument suite's increased sensitive to disturbances over a broad spectrum 0-512 Hz. Sources of disturbance include reaction wheels, thruster firings for station keeping and momentum management, gimbal motion, and internal instrument disturbances. To minimize the impact of these disturbances, the baseline design includes an Earth Pointed Platform (EPP), a stiff optical bench to which the two nadir pointed instruments are collocated together with the Guidance Navigation & Control (GN&C) star trackers and Inertial Measurement Units (IMUs). The EPP is passively isolated from the spacecraft bus with Honeywell D-Strut isolators providing attenuation for frequencies above ~5 Hz in all six degrees-of-freedom. A change in Reaction Wheel Assembly (RWA) vendors occurred very late in the program. To reduce the risk of RWA disturbances impacting performance, a secondary passive isolation system manufactured by Moog CSA Engineering was incorporated under each of the six 160 Nms RWAs, tuned to provide attenuation at frequencies above ~50 Hz. Integrated wheel and isolator testing was performed on a Kistler table at NASA Goddard Space Flight Center. High fidelity simulations were conducted to evaluate jitter performance for four topologies: 1) hard mounted no isolation, 2) EPP isolation only, 2) RWA isolation only, and 4) dual isolation. Simulation results demonstrate excellent performance relative to the pointing stability requirements, with dual isolated Line of Sight (LOS) jitter <1 μ rad.

INTRODUCTION

GOES-R is the first in a new generation of U.S. geostationary weather satellites managed collaboratively by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA). Assembled by Lockheed Martin Space Systems in Denver, the satellite is scheduled for launch in March 2016 and will include next generation Earth-observing instruments. The Advanced Baseline Imager (ABI), represents a

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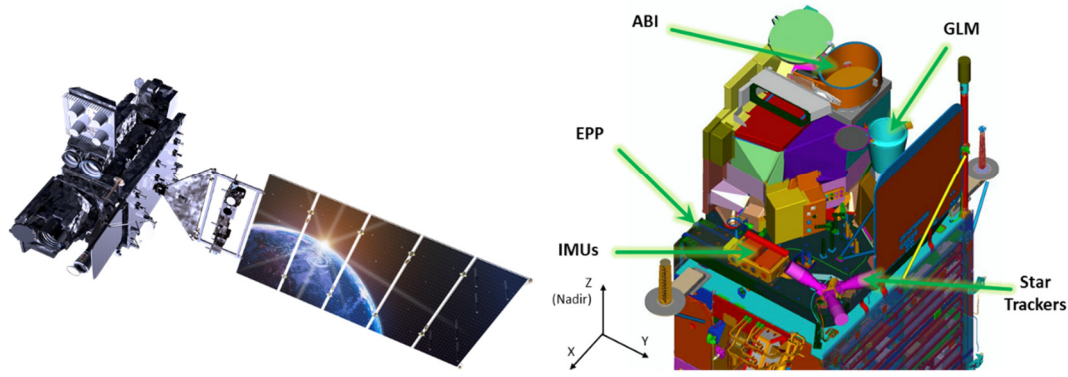
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dramatic increase in Earth weather observation capabilities with 4 times the resolution, 5 times the observation rate and 3 times the number of spectral bands over existing sensors. In addition, a brand new Earth-observing instrument the Geostationary Lightning Mapper (GLM) is also hosted. GLM is a near-infrared optical transient detector, which can detect extremely brief changes in an optical scene, indicating the presence of lightning. Both ABI and GLM are nadir pointed instruments residing on the satellite's Earth Pointed Platform (EPP) as shown in Figure 1.

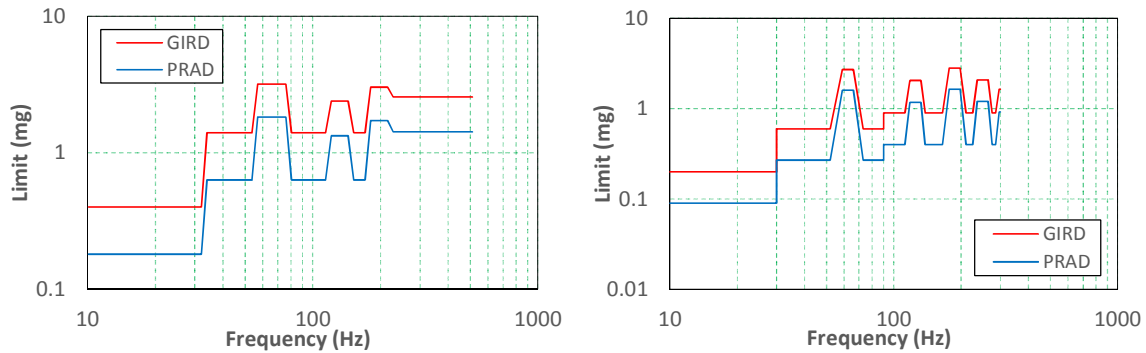


a) Operational configuration.

b) EPP layout.

Figure 1. GOES-R spacecraft on-orbit operational configuration and EPP layout.¹

The increased spatial, spectral and temporal resolution of the GOES-R Earth-observing instruments impose extremely demanding GN&C performance requirements including attitude knowledge, Integrated Rate Error (IRE), orbit knowledge, pointing accuracy, pointing stability, and jitter. Germaine to our discussions here are the jitter requirements, cast in terms of the linear translational accelerations and Shock Response Spectra (SRS) at the instrument interfaces, as shown in Figure 2. Two levels are shown, General Interface Requirements Document (GIRD) and Payload Resource Allocation Document (PRAD).^{2,3} The instruments are designed to meet their performance requirements in the presences of the higher GIRD levels. The spacecraft is designed to produce disturbances no greater than the lower PRAD levels. The difference between the two levels is government reserve. The requirements cover a broad frequency range out to 512 Hz, which drives the EPP optical bench to be a stiff design, passively isolated from the spacecraft bus.



a) Linear translation acceleration limits.

b) Shock response spectra limits.

Figure 2. Jitter requirements are cast in terms of acceleration and SRS at the instrument interface.

The EPP attenuates bus disturbances to the Earth-observing instruments, passively isolated from the spacecraft bus with Honeywell D-Strut isolators providing attenuation for frequencies above ~5 Hz. Originally this configuration was sufficient to provide isolation from all spacecraft bus disturbances including the Goodrich Type-E RWA disturbances, gimbal disturbances and disturbances from the sun-pointed instruments. However, the acquisition of Goodrich by United

Technologies and the subsequent decision to close down manufacturing in Ithaca was seen as a high risk to the Flight Project. To mitigate this risk, with less than 14 months to critical path need date, a parallel acquisition was initiated with Honeywell for their HR-18 Constellation Series RWA. Ultimately the HR-18 acquisition matured faster and was consequently selected. Testing of the Engineering Design Unit (EDU) RWA on a Kistler table at NASA Goddard confirmed a resonant at 230 Hz not present in the Goodrich wheel, Figure 3. To reduce the risk of RWA disturbances impacting performance, a secondary passive isolation system manufactured by Moog CSA Engineering was incorporated under each of the six RWAs tuned to provide attenuation at frequencies >50 Hz.

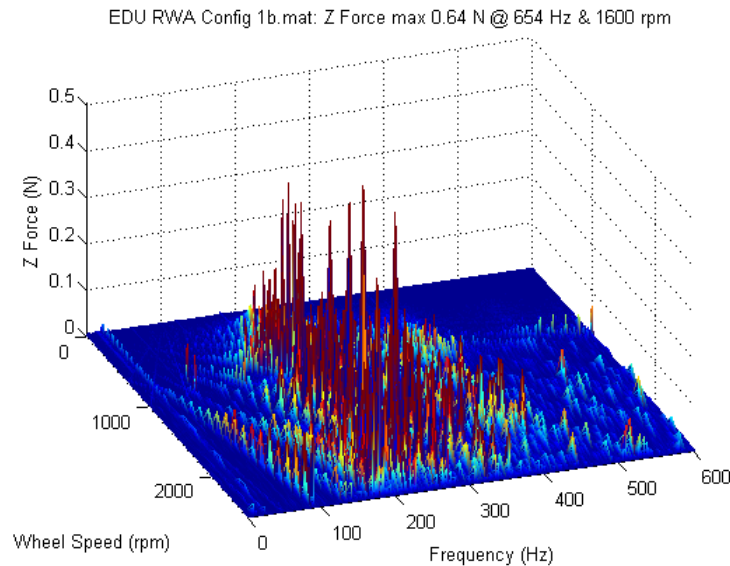


Figure 3. NASA Goddard EDU RWA Kistler table induced vibration measurements.

In this paper we present a description of the dual EPP and RWA isolation systems and how they work together to satisfy mission requirements. A description of EPP isolation is provided together with EDU test results. Likewise, a description of RWA isolation and EDU test results are provided. System level performance is evaluated using high fidelity simulations including a comparison of four topologies: 1) hard mount no isolation, 2) EPP isolation only, 2) RWA isolation only, and 4) dual isolation. We discuss system level testing that will validate the jitter modeling approach and provide confidence that the on-orbit jitter response requirements will be met. Finally, we provide insight into planned on-orbit performance evaluation with the EPP both stowed and deployed.

EPP ISOLATION AND TESTING

The EPP provides a stable platform for the two Earth-observing instruments, ABI and GLM, and the attitude determination sensors, Northrop-Grumman SSIRUs and SODERN Hydra star trackers. The EPP implementation provides quasi-kinematic mechanical mounting of the instruments, power and data interfaces, grounding, and thermal interfaces. The key requirements imposed upon the EPP design are pointing stability and alignment stability of the instruments and Attitude Determination (AD) sensors. Alignment stability requirements are extremely tight; changes due to thermal distortion are budgeted to be less than 30 μ rad over an orbit.

The EPP is constructed as a composite sandwich panel with an overall thickness of \sim 15.3 cm. The facesheets are carbon fiber, and the core is aluminum honeycomb with density variations as required for strength and stiffness. The dimensions of the EPP are approximately 188 cm x 218 cm. The overall mass of the EPP and fittings is approximately 145 kg, and the total mass of the

EPP platform with all the components and instruments installed is approximately 530 kg. To achieve the pointing and alignment stability requirements, the EPP is very stiff—the first mode of the deployed EPP with the components and instruments installed is greater than 50 Hz. Figure 4 shows the overall configuration of the populated EPP.



Figure 4. GOES-R EPP populated with instruments and AD sensors.

The high stiffness of the optical bench readily transmits disturbances through the structure. To attenuate high frequency disturbances to the Earth-observing instruments from the spacecraft bus, including reaction wheel disturbances, gimbal disturbances, and disturbances from the sun-pointed instruments, the EPP is passively isolated from the spacecraft bus with flight-proven Honeywell D-Strut isolators arranged in a modified Stewart platform configuration.⁴ The isolation system provides attenuation for frequencies above ~ 5 Hz in all six degrees-of-freedom. The mounting geometry and the strut parameters have been optimized to provide balanced isolation performance in all six degrees-of-freedom. The Honeywell isolator design provides linear, predictable behavior with low temperature sensitivity. Because of the large mass of the populated EPP, the isolation system travel capability is relatively modest. The required travel for each of the 6 isolators is only 1.5 mm. The deployed isolation system is not capable of surviving the launch loads. Therefore, a set of 4 launch locks secures the EPP platform to the spacecraft bus until the final geosynchronous orbit is achieved.

The GOES-R program established requirements for the EPP isolation based upon simulations of the vehicle disturbances and the transmissibility of the structure. Because of the uncertainties inherent in the early phases of the design effort, these models used to derive the isolation requirements included conservative modeling assumptions. Details of the modeling and analysis approach have been presented by Chapel, et al.¹ The resulting requirements include a 2nd-order roll-off with a center frequency of ~ 5 Hz, and span a frequency range from 1 Hz to 30 Hz. The peaking of the isolation system is limited to less than 6 dB. The subsequent X and Y-axis isolation envelopes are shown in Figure 6. These requirements apply to each of the six degrees-of-freedom, and apply over the operational temperature range.

The GOES-R program undertook a full qualification effort for the EPP and the EPP isolation system. To demonstrate acceptable stability and isolation performance and to validate the simulation models, an EDU EPP with six D-Strut isolators arranged in a flight-like configuration was assembled and tested at Honeywell's facilities. This test configuration is shown in Figure 5. The test configuration included mass simulators for the ABI and GLM instruments, as well as the GLM radiator. Mass simulators were also included for the star trackers and IMUs. To assess the

isolator performance impacts of parasitic shunts across the isolation interface, flight-like harnessing and multi-layer insulation blanketing were also included in the test configuration. Tests were run with and without the shunts present.

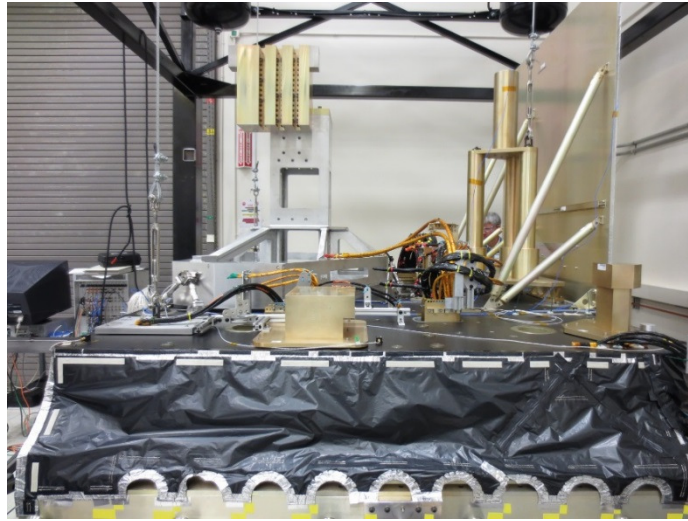


Figure 5. GOES-R EPP EDU populated with mass simulators and parasitic shunt elements.

The transmissibility results of the EPP EDU testing are shown in Figure 6 for the X and Y translation axes. As can be seen in the figure, the requirements are met for the EPP isolation with and without the shunts included. However, the shunts clearly affect the performance of the isolation system, and therefore cannot be neglected in the simulation models. The peaking of the isolation increases by up to 50%, and the center frequency shifts higher by up to 20%. The shunts are not symmetric with respect to the EPP layout, so some axes are affected more than others. Because of the impacts of the shunts on the overall dynamics, additional testing was performed to more accurately capture the shunts' effects. The results have been included in the high-fidelity simulation models of the EPP isolation.

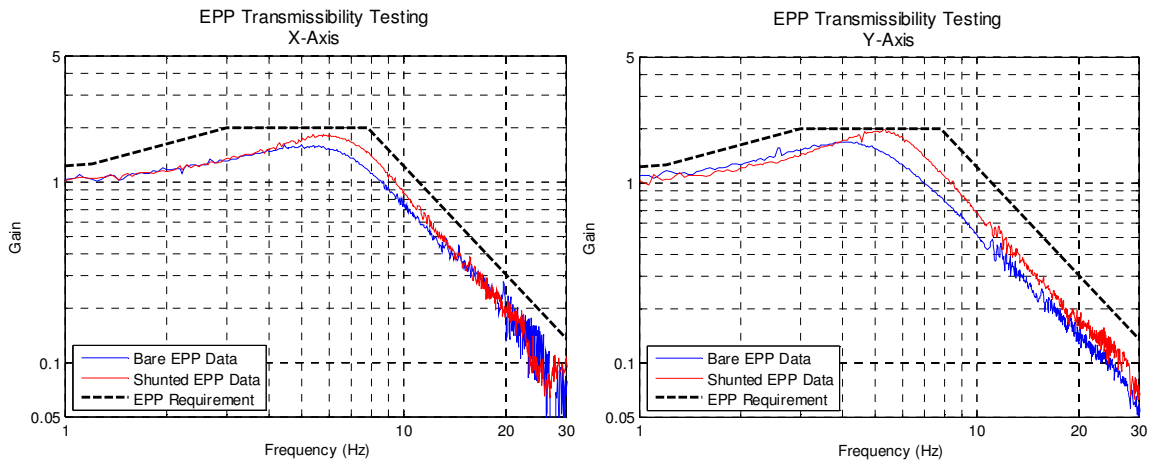


Figure 6. GOES-R EPP isolation requirements and observed performance from EDU testing.⁵

RWA ISOLATION AND TESTING

RWA Isolation

The RWA isolation system was designed by Moog CSA to directly isolate the disturbance source and to work in concert with the EPP isolation system. All six GOES-R RWA wheels were isolated independently; each by a system of three isolators positioned between the RWA adapter and pedestal as seen in Figure 7. As with all isolation systems, the ability to cluster the six isolation modes into a frequency band that does not: 1) couple with wheel disturbance frequencies and, 2) interfere with spacecraft bus resonances that could exacerbate the LOS jitter issues already established, is key. Flight hardware was delivered in nine months.

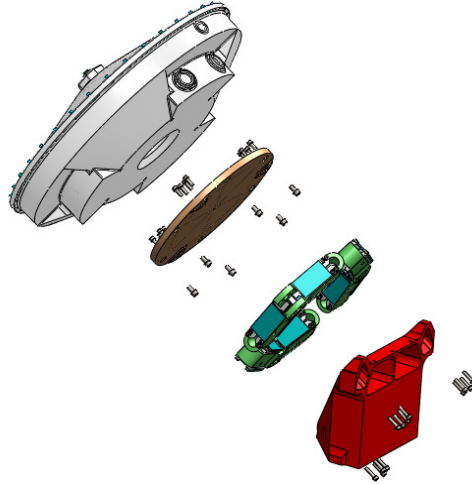


Figure 7. RWA isolation system assembly, single wheel.

The compliance element of the RWA isolation system is centered on Moog CSA's heritage technology: a metallic flexure based compliant element with viscoelastic material (VEM) constrained layer damping.^{6,7} The form factor of both components were custom designed and tuned to provide the desired performance in all degrees of freedom (DOF).

Tuning stiffness of the isolator was done by manipulating parameters of the titanium flexure. The flexure is the primary load path of the isolator and therefore the primary stiffness element. This flexure is a direct evolutionary descendent of the SoftRide MultiFlex design.⁸ The flexure requires no launch lock and has the additional advantage of softening the launch environment. Each of the three translation stiffness characteristics are not only observed, but tuned to achieve the desired suspension mode frequencies of the system.

The VEM provides damping. As with all viscoelastic materials, stiffness and loss are temperature, humidity, and frequency dependent. Therefore, the isolator stiffness and damping performance is also temperature, humidity, and frequency dependent. All operating environments, both during launch and on-orbit, were considered when designing and evaluating the performance of the isolation system. Knowledge of these material properties are required develop reliable a system with reliable and predictable performance characteristics in all operational environments.

The switch to the larger HR18 RWA resulted in a depletion of design space for modifications and optimal tuning of the RWA isolation system. Specifically, the RWA sled and RWA bay in the spacecraft bus was designed to accommodate a smaller wheel. The pedestal was redesigned in conjunction with the isolators to allow for a 41 mm isolator stack height. The system of three isolators was required to stay within a diameter of 267 mm. Therefore, the isolator was designed with a low profile and canted blade flexure.

Within this space constrained package, the team was able to develop a system that complied with the minimum frequency requirement of 45 Hz, met the damping requirements of 3% critical damping in the suspension modes, and was tuned to provide 6 DOF isolation. Lastly, the required attenuation beyond the break frequency was achieved per the specification.

Measured data along the RWA spin axis from modal testing of an RWA mass simulator on the isolator system is shown in Figure 8. The transmissibility data shows attenuation of disturbance input with the system rejecting 90% of the disturbances above 350 Hz.

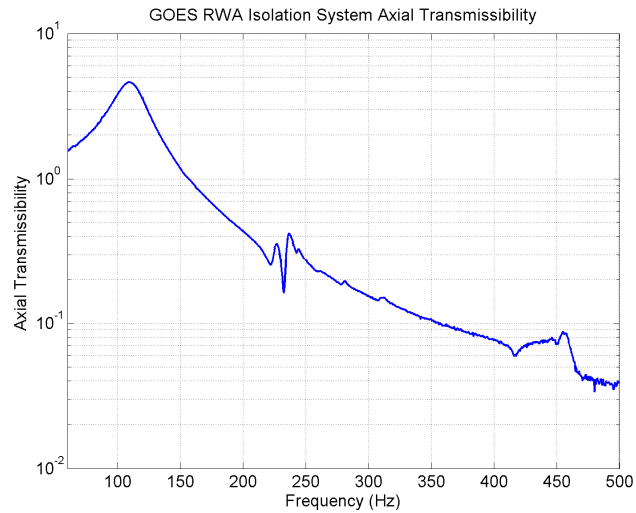


Figure 8. Measured RWA isolator spin axis transmissibility.

Integrated RWA and Isolator Kistler Table Testing

As Honeywell completed EDU RWA testing and Moog/CSA completed EDU isolator testing, the separate elements were shipped to NASA Goddard for integrated testing on a Kistler Table. This would be the only time the RWA and isolator were tested as an integrated unit, Figure 9. Testing was performed in the five different configurations listed in Table 1. Kistler table accuracy was verified using a calibrated hammer.

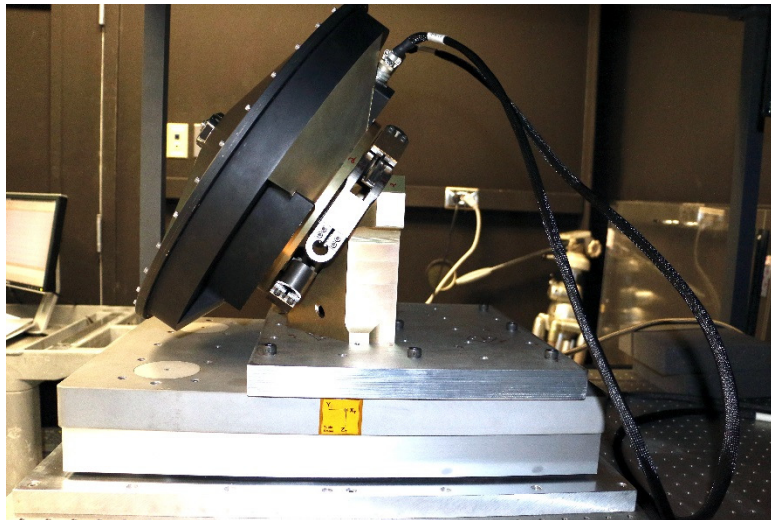


Figure 9. Integrated RWA and isolator on Kistler table for induced vibration measurement testing at NASA Goddard (Configuration 4).

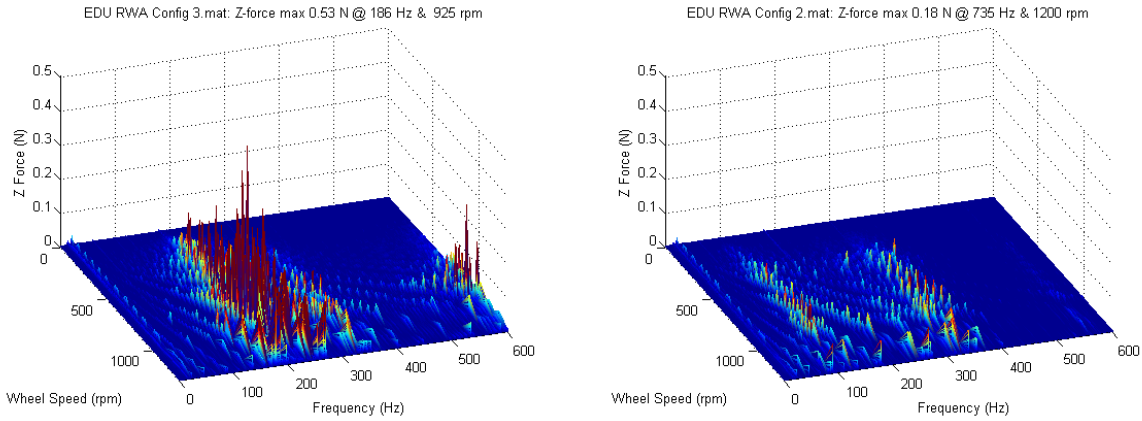
Table 1. Integrated RWA and Isolator Kistler Table Test Configurations

Configuration	System	Data Acquisition			
		RWA Tach Signal	Sample Rate (kHz)	Low Pass Filter (kHz)	
1	RWA	Lab View	No	1.6	0.3
2	RWA Adapter Plate Isolator	OROS	Yes	10.24	1
3	RWA Adapter Plate Hard Mount	OROS	Yes	10.24	1
4	RWA Adapter Plate Isolator Pedestal	OROS	Yes	10.24	1
5	RWA Adapter Plate Hard Mount Pedestal	OROS	Yes	10.24	1

Configuration 1. This configuration tested the RWA by itself, allowing a comparison of Goddard’s results with those obtained by Honeywell. It assured that the Kistler table and data acquisition system were functioning properly, and allowed checkout of procedures that would be repeated for all other tests. The Lab View data acquisition system was limited to 8 channels with a maximum sample rate and anti-alias filter of 1,600/300 Hz respectively. Needing to add the RWA tach signal and increase the sampling to 10,240 Hz allowing us to push the anti-alias filter out to 1000 Hz, all subsequent testing was performed using an OROS data acquisition system.

Configuration 2 and 3. These configurations were identical with the exception that in configuration 2 the RWA was mounted on the Moog/CSA isolators while configuration 3 had the RWA hard mounted. The hard mounts were designed to keep the RWA CG at exactly the same location relative to the Kistler table. The measured Z-axis (RWA spin axis) force disturbances over the nominal operational wheel speed range 0-1300 RPM are shown in Figure 10 for both the hard mounted and isolated configurations. The improvement in performance over the 200-300 Hz band is consistent with that measured by the Moog CSA modal testing, Figure 8.

Configuration 4 and 5. These configurations tested the RWA mounted on a pedestal in a flight like orientation, Figure 9. The configurations were identical with the exception that configuration 4 included the isolators while configuration 5 included the hard mounts.



a) Hard mount configuration 3.

b) Isolated configuration 2.

Figure 10. RWA hard mount vs isolated NASA Goddard Kistler table induced vibration results.

SYSTEM PERFORMANCE ANALYSIS

The GOES-R high-fidelity observatory pointing control and jitter simulation was developed from high-fidelity structural dynamics component models, integrated into a system level structural model using component modes synthesis. The modal content of the combined observatory structural model was adequate to characterize observatory flexibility up to 512 Hz. The model was augmented with physics-based nonlinear phenomenon and multi-rate control loops. The model implements disturbances resulting from RWAs, thruster firings, thermal snaps, solar array articulation, and others. The high-fidelity observatory pointing control and jitter simulation was used to analytically verify GOES-R on-orbit pointing control and jitter performance requirements. The integrated model includes:

- All instrument models: ABI, GLM, SUVI, EXIS, SEISS
- Honeywell EPP and isolation mount system
- Reaction wheels and reaction wheel brackets with isolation
- Deployed magnetometer boom and magnetometers
- Deployed solar array wing, antenna wing, and X-Band antenna reflector
- Propellant slosh dynamics
- Engineering Diagnostic Accelerometers (EDA) models
- Nadir instrument LOS models

The high-fidelity observatory jitter simulation development yielded a model with nearly ten-thousand states, nonlinear employing high-fidelity friction components, and hybrid-time. High-level sensitivity analyses based on topological modifications lends credibility to the model. These topological changes confirmed that the model behaved in a predetermined expected manner. The model topological sensitivity analysis also confirmed the model's robustness to credible model changes.

The high-fidelity simulation was exercised to evaluate performance of four topologies selected to gain insight into the effectiveness of isolation. The four topologies included:

- Dual Hard Mount
- EPP Isolation Only
- RWA Isolation Only
- Dual Isolation

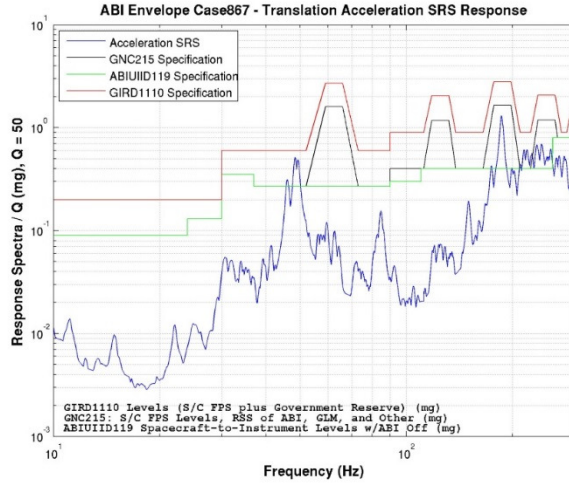
There are six EDAs mounted on the EPP to measure accelerations at the ABI and GLM instrument interfaces on-orbit. They are modeled in the high-fidelity observatory jitter model. The frequency spectrum produced by the EDA models serve as the performance metrics. Translation acceleration SRS responses are shown in Figure 11 for the four topologies. These results apply for the ABI off scenario to better assess the bus-borne disturbance impacts on the EPP disturbance perturbation environment. As expected, the dual hard mounted topology with no isolation produces the largest disturbances, serving as a baseline for comparison Figure 11a. Relative to the dual hard mount topology, the EPP isolation-only topology (Figure 11b) shows enhanced disturbance isolation characteristics in the mid-frequency range but less so at the higher frequencies, where the RWA emitted disturbances are more influential. This EPP isolation-only characteristic agrees with expectations for a well damped ~5 Hz type second-order mechanical isolator with a response that flattens out at higher frequencies. The RWA isolation only topology (Figure 11c) shows enhanced isolation at the higher frequency range, where the RWA disturbances are more influential, but less disturbance isolation in the mid-frequency range relative to the dual hard mount topology. This RWA isolation-only characteristic agrees with expectations for a well damped 60 Hz type mechanical isolator. The dual isolation (Figure 11d) exhibits the expected broad band disturbance

isolation characteristic above ~5 Hz and is the result of the EPP and RWA isolators operating in tandem.

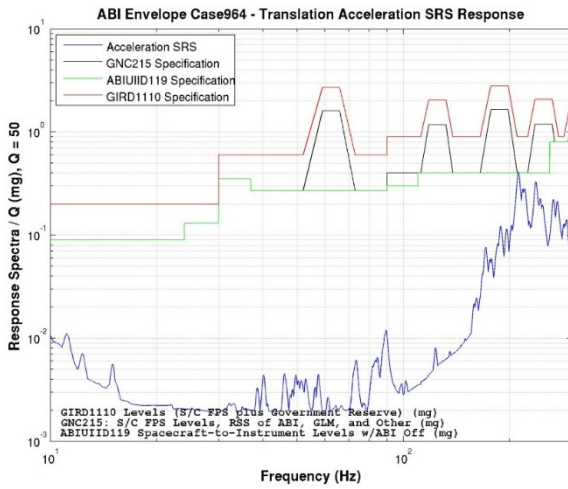
The ABI and GLM LOS pointing performance, although not specified as a requirement, tends to add confidence that requirements will be satisfied. These LOSs are produced with the use of optical sensitivity matrices tied to the structural deformation of optical node points resulting from the applied disturbances. Results for the ABI LOS pointing errors are summarized in Table 2. The dual hard mount topology results in the greatest LOS error. Both the EPP isolation only and RWA isolation only topologies result in comparable improvements over hard mount. Dual isolation results in the best performance.

Table 2. ABI LOS Pointing Error

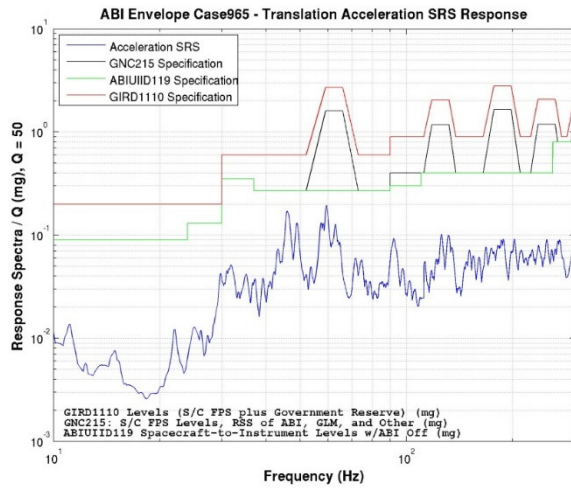
Topology	3-Sigma		Peak	
	North/South	East/West	North/South	East/West
	(μ rad)	(μ rad)	(μ rad)	(μ rad)
Dual Hard Mount	0.448	0.351	0.860	0.668
EPP Isolation Only	0.296	0.291	0.510	0.474
RWA Isolation Only	0.296	0.291	0.513	0.474
Dual Isolation	0.286	0.285	0.477	0.465



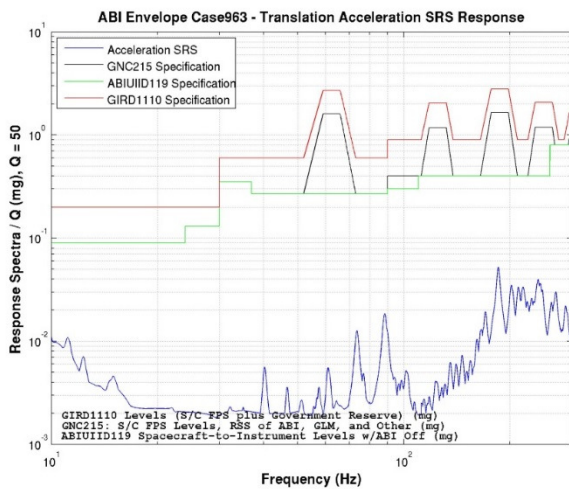
a) Dual hard mount.



b) EPP only isolation.



c) RWA only isolation.



d) Dual hard mount.

Figure 11. Translation acceleration SRS response.

SYSTEM LEVEL TESTING

System level testing includes a pre-launch Dynamic Interaction Test (DIT) as well as Post Launch Testing (PLT). The pre-launch DIT is mandated by the spacecraft statement of work.⁹ The DIT measures structural dynamic responses due to instrument and satellite disturbance sources to validate the dynamic models of the satellite, characterizing the integrated spacecraft dynamics in a flight-like configuration for the nadir pointed ABI and GLM instruments. The DIT does not verify performance. Rather, the DIT demonstrates that observatory dynamic responses are in family with predictions, establishing confidence that the disturbance and damping elements of the system design are functioning as expected.

Figure 12 illustrates how the EPP is offloaded during the DIT. To achieve a flight configuration requires the use of an Anti-Gravity Machine (AGM) supplied by Moog CSA Engineering. In addition to the flight EDAs, during the tests the spacecraft will be instrumented with high bandwidth linear acceleration sensors collected at 2000 Hz to verify accelerations during operations with RWA and instrument disturbances.

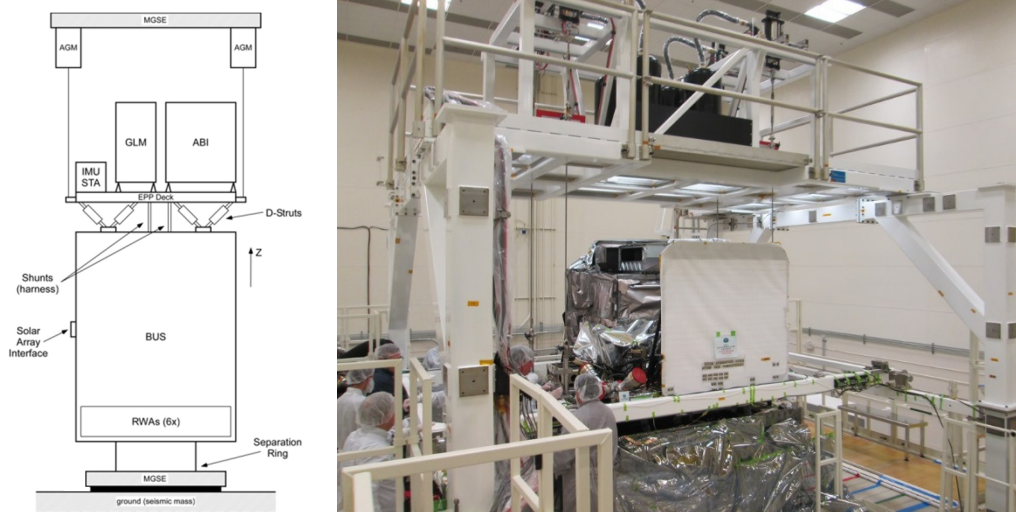


Figure 12. AGM offloads EPP during deployment and DIT.

Following launch GOES-R will undergo 6 months of extensive testing prior to being put into operational service. The testing will include: 1) characterization of the disturbance environment at the ABI and GLM interfaces using the EDAs and 2) an assessment of the quality of the actual ABI and GLM data products. A key element of this testing is that data will be collected both prior to the release of the EPP launch locks (hard mounted), and following EPP deployment (isolated). As the analysis suggest, it is fully expected that performance with the EPP hard mounted and RWA isolated, mission requirements will be satisfied.

CONCLUSION

Missions with stringent jitter requirements are often faced with the dilemma of isolating the payload sensitive to jitter, or isolating the source of the jitter itself. In this paper we have shown how we solved this dilemma electing a minimum risk, albeit not minimum cost, dual isolation system for GOES-R. We have shown how EPP isolation provides the necessary attenuation at lower frequencies and how RWA isolation provides the necessary attenuation at higher frequencies. A priori knowledge of the disturbance environment and payload LOS sensitivities to jitter are the key. Hindsight is 20/20 but the simulation results show that for GOES-R either would have sufficed. Had we known from the start that: 1) we would fly the HR-18 RWA, 2) had a detailed understanding of payload dynamics, and 3) been less conservative in our modeling of predicted

parasitic shunt loads and damping, our solution may have been different. DIT testing will provide additional insight prior to launch, but the truth will be revealed during on-orbit testing where we will have the unique opportunity to evaluate jitter performance with the EPP both stowed and deployed. These actual performance data may give us pause to re-evaluate GOES-T and GOES-U isolation.

ACKNOWLEDGMENT

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