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A SURVEY OF THE SPACECRAFT LINE-OF-SIGHT JITTER PROBLEM

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Predicting, managing, controlling, and testing spacecraft Line-of-Sight (LoS) jitter due to on-board internal disturbance sources is a challenging multi-disciplinary systems engineering problem, especially for those observatories hosting extremely sensitive optical sensor payloads with stringent requirements on allowable LoS jitter. Some specific spacecraft jitter engineering challenges will be introduced and described in this survey paper. Illustrative examples of missions where dynamic interactions have to be addressed to satisfy demanding payload instrument LoS jitter requirements will be provided. Some lessons learned and a set of recommended rules of thumb are also presented to provide guidance for analysts on where to initiate and how to approach a new spacecraft jitter design problem. These experience-based spacecraft jitter lessons learned and rules of thumb are provided in the hope they can be leveraged on new space system development projects to help overcome unfamiliarity with previously identified jitter technical pitfalls and challenges.

THE JITTER PROBLEM

In the formulation of next generation of space and Earth science missions, there is a constant trend by both National Aeronautics and Space Administration (NASA) to push towards higher performing payloads and instruments. This manifests itself in increasingly demanding requirements for science/observational instrument resolution, pointing stability, lower sensor operating temperatures, etc. The trend with more capable systems will generally be towards increased detector resolution and sensitivity, sometimes leading to greater dwell time, usually leading to tighter pointing requirements. Next generation imaging system requirements for increased Focal Plane Array (FPA) resolution and longer integration time can directly drive associated requirements for higher instrument pointing stability and allowable Line-of-Sight (LoS) jitter. Likewise, the need for operating instruments and sensors at much colder operating temperatures will likely drive a need for on-board cryocoolers that will introduce pointing disturbances.

NASA is currently planning spaceflight missions that include high-performance optical payloads with highly vibration-sensitive scientific/observational instruments. The types of missions included here span both space science and Earth observation applications. Control of jitter is also critical for stabilizing optical communications payloads, another very demanding mission application. Often the goals and objectives of these missions result in rigorous and challenging requirements on the design of the observatory (i.e., the spacecraft bus plus the optical payload) to provide precise bus pointing and mechanically quiet science instrument accommodations in the face of dynamic interactions.

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In particular, these instrument accommodation requirements often manifest themselves as very stringent, arcsecond (arcsec) level or less, constraints on attitude stability and rate stability at the instrument interface with the spacecraft over a vastly extended frequency range well beyond the Attitude Control System (ACS) bandwidth. The inherent lightweight nature of these observatory structures and the resulting multitude of closely spaced, lightly damped, low-frequency flexible body modes of vibration, as well as the variety of higher frequency disturbance sources, make meeting these challenging engineering requirements very demanding. Thus, it is not surprising that the technical challenges associated with understanding, managing, and controlling observatory dynamic interactions that create jitter have now risen in prominence to form one of the most daunting and critically important spacecraft systems engineering problem areas.

For the purposes of this paper, spacecraft LoS jitter is defined as the small-amplitude sinusoidal mechanical vibrations occurring due to dynamic interactions caused by vibrating mechanical devices either mounted on the spacecraft bus or within the payload instrument(s) that appear at frequencies at or above the spacecraft's ACS bandwidth from a few Hz up to a few hundred Hz and that undesirably perturb spacecraft LoS jitter are the LoS pointing of a spacecraft-mounted payload instrument(s). This is a slightly modified version of the jitter definition provided in Reference 1.

The performance impact of jitter is clearly depicted in Figure 1 (taken directly from Reference 1) where the time-varying LoS pointing is illustrated in the left portion of the figure. The right potion of Figure 1 then compares the relative quality of three separate images, which viewed from left to right, portray: the image taken when significant jitter perturbations were present, the image when some corrective measures had been applied to mitigate the perturbing jitter effects, and lastly when the imager LoS was undisturbed during the image-taking period.

NASA, together with their industry partners, have a long, technically rich, and impressive history of successfully addressing the spacecraft engineering problems associated with managing undesirable dynamic interactions that perturb an observatory's payload instrument pointing/pointing stability (aka "jitter"). This jitter engineering history can be traced as far back as the mid-1970s when NASA was studying architectural concepts for the so-called Large Space Telescope (LST), which was to later become much better known as the Hubble Space Telescope (HST).

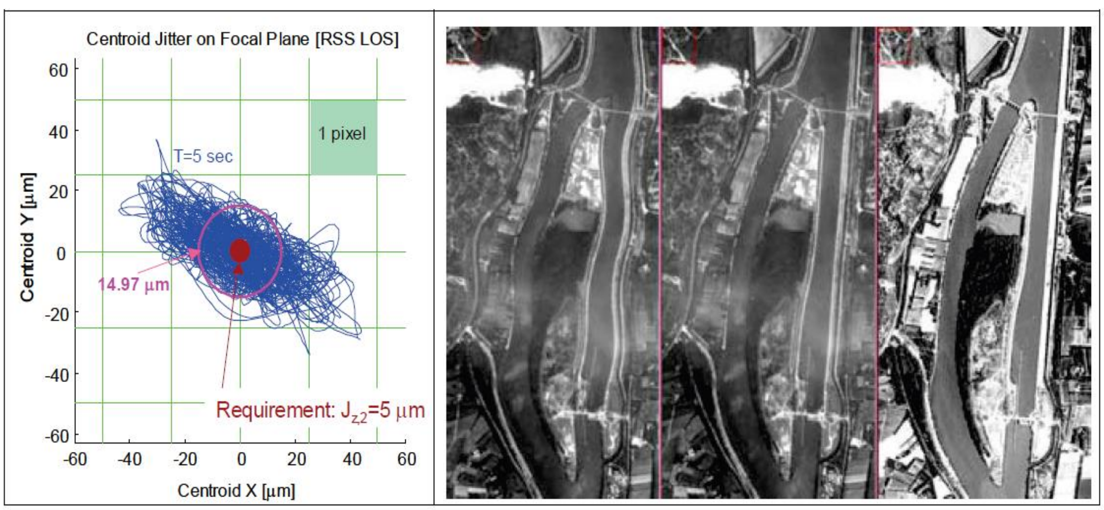

Figure 1. Example of LoS Pointing Errors and the Resulting Effects on Image Quality (from Reference 1).

Readers with an interest in an insightful historical discussion of spacecraft jitter engineering over the last four decades are directed to Reference 2, where this important history is provided in the form of a detailed and valuable technical literature review.[2] Additionally some excellent discussion into the jitter problem is provided in References 3 and 4 where two different mission perspectives on methods and approaches for managing the spacecraft jitter problem are explained in detail.[3 4]

Jitter is generated by internal mechanisms/mechanical devices placed on-board the observatory. These disturbance-generating devices typically include internally rotating mechanisms such as a Reaction Wheel (RW) and/or a Momentum Wheel (MW), which are almost always located on the spacecraft bus. Other jitter sources include payload-generated excitations from sensor cryocoolers and cryopumps, as well as instrument-internal mechanisms such as scanning mirrors, steering mirrors, and filter wheel mechanisms. Disturbances can also arise from the use of High Gain Antenna (HGA) and or Solar Array (SA) drive mechanisms, appendage gimbal drives/pointing mechanisms, and attitude control/momentum dumping thrusters. Propellant sloshing and control-structures interactions may also contribute to the spacecraft's internal disturbance environment and can potentially excite jitter at a critical payload instrument location.

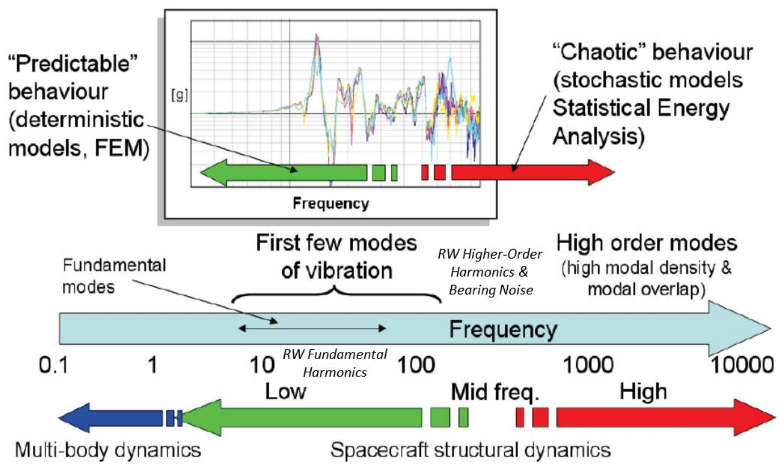

Figure 2. Spacecraft Dynamic Behavior and Analysis Methodologies Over Broad Frequency Range (from Reference 1).

One aspect that makes the spacecraft jitter problem organizationally challenging is the fact that it is a true observatory-level problem involving multiple engineering disciplines: Structures; Mechanisms and Mechanical Systems; Guidance, Navigation and Control (GN&C); Loads and Dynamics; and of course, System Engineering. Typically, another complicating factor, especially on the larger and more complex missions, is the many organizational interactions needed across the government-industry-science project team. As depicted in Figure 3 there are multiple inter-related technical aspects to solving the spacecraft jitter problem. These result in the need for: many forms of technical analyses, the development of many models, and many forms of testing. These inter-related activities will occur over the entire project lifecycle from Formulation Phase to Flight Operations Phase. This jitter modeling, analysis, and testing work necessarily overlaps traditional spacecraft subsystem boundaries and requires observatory-level management, cross-discipline communications, and overall coordination for mission success. While multiple organizations are typically involved, the leadership in understanding jitter issues usually comes from Systems Engineering, GN&C and/or the Mechanisms and Mechanical Systems technical staff.

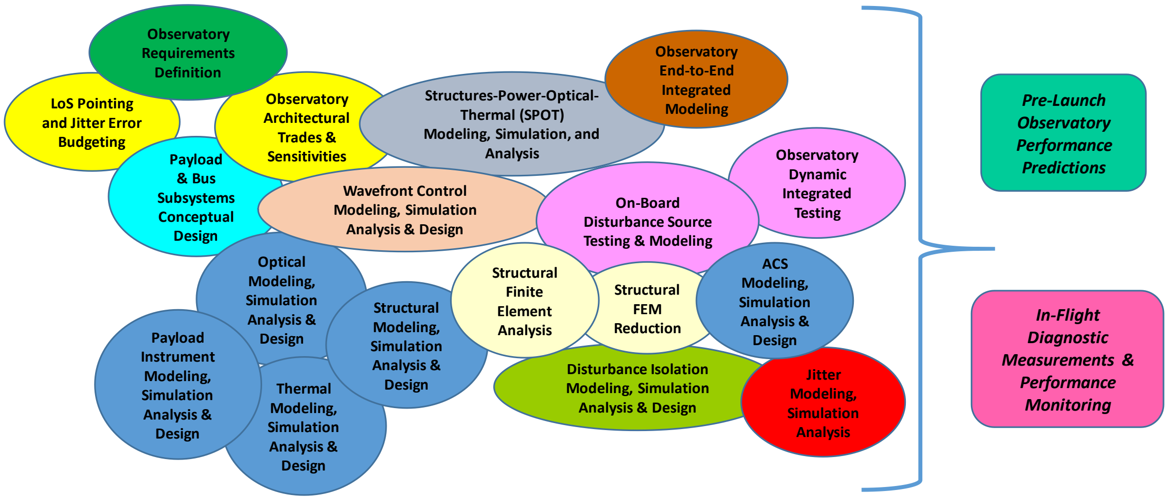

Figure 3. Many Requirements, Many Disciplines, Many Analyses, Many Models, and Many Tests over the Entire Project Lifecycle.

SOME ILLUSTRATIVE OBSERVATORY LOS JITTER EXPERIENCES

The following are short survey-level descriptions that highlight the various types of LoS jitter experiences caused by undesirable dynamic interactions, which have occurred on some selected NASA missions. Readers are directed to Reference 5 for several additional illustrative real-world LoS jitter problems.

Hubble Space Telescope (HST)

The Hubble Space Telescope (HST) observatory, the first of NASA's so-called Great Observatories, was deployed on 25 April 1990 from the Space Shuttle Orbiter Discovery into a 332-nmi Earth orbit. The HST was designed to achieve stringent LoS pointing stability while observing celestial objects for long exposures. At the highest-level, the telescope's pointing requirement was specified at <7 milli-arcsecond (mas) over a 24-hour period.

As described in References 6 through 9, the Pointing Control System (PCS) for this ground-breaking, one-of-a-kind space-based observatory was carefully designed to stabilize the SA and coupled vehicle-telescope bending modes.[6,7,8,9] Not surprisingly significant resources were devoted to performing pre-launch jitter analysis and prediction, much of it focused on disturbance source modeling and characterization to understand the potential impacts on the telescope's LoS jitter. As described in Reference 10, the initial HST jitter studies at the prime contractor, which were based upon historical approaches used by the contractor on classified satellites, were devoted to predicting disturbance effects on a LoS central pointing vector along with minimizing other known image-distorting effects.[10] An additional design goal was to ensure a large separation of the primary structural mode frequencies from the maximum active control bandwidth frequency. The prime contractor also developed a full-scale Structural Dynamics Test Vehicle (SDTV). The SDTV was a medium-fidelity demonstrator assembled with flight-like structural components. In addition, as also described in Reference 10, an unprecedented set of high-sensitivity induced vibration data was acquired for each of the five flight-certified RWs used in the PCS. Ultimately, a Dynamic Interaction Test (DIT) of the full-up HST observatory, suspended by bungee-cord-like devices to off-load gravity, was performed in the prime contractor's test facility to more fully characterize the telescope's susceptibility to jitter disturbances. In order to demonstrate the required level of performance, multiple city blocks around the prime contractor's test facility were effectively shut down from vehicular traffic.

Not long after its on-orbit activation, problems were experienced that severely impacted the HST's capability to perform its mission. Not only was an optical flaw discovered in the telescope's main mirror, but also examination of the real-time flight telemetry data revealed that the HST was experiencing unexpectedly large disturbances that were most pronounced as the spacecraft entered or left the Earth's shadow. A focused effort to investigate the nature of the observed pointing disturbances identified the SAs as the source of the disturbance. The thermal/mechanical energy in the arrays was being stored and released in such a manner as to excite the primary modes of the arrays. The PCS, as initially designed, was unable to compensate for these unexpected pointing perturbations due to the so-called Sunrise/Sunset 'thermal snap' SA disturbances.

As soon as the problem was identified, efforts to redesign the PCS to eliminate the effects of the disturbances began. A successful reconfiguration of the flight computer and redesign of the control system, along with a slight modification of the original performance requirements, resulted in a controller that met the new specifications most of the time. Because of the PCS redesign efforts, a wealth of flight data were collected that was specific to the control system performance. Simulation models were enhanced as more was learned about the on-orbit dynamic behavior of the spacecraft. Techniques were developed to explore the behavior and performance of new controller designs using actual flight data to simulate the disturbances imparted on to HST by the flexible SAs. To take maximum advantage of the data and simulations available, a design study was initiated. The excellent engineering work highlighted above to recover HST pointing performance is described in detail in References 11 through 15.[11,12,13,14,15]

Later in its mission, another HST jitter issue surfaced concerning the pointing disturbance caused by the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) Cryo Cooler (NCC). The NCC is a single-stage reverse Brayton cycle system using micro turbo-machinery to provide necessary cooling to the detectors of the NICMOS infrared science instrument. The NCC was installed in March 2002 during the HST Servicing Mission 3B (SM3B). Ground testing and analytical predictions for HST on-orbit jitter levels after SM3B, with all disturbance sources active, indicated that the NCC would be the predominant disturbance source generating significant jitter for HST. Therefore, as described in References 16 and 17, there was extensive testing conducted to quantify the expected on-orbit disturbances caused by the micro turbo-machinery.[16,17]

Chandra

The Chandra science observatory was launched in July of 1999. The third of NASA's Great Observatories, Chandra's primary mission is to address some of the most fundamental questions in present-day astrophysics through observations of X-rays. A detailed description of Chandra's Imaging Pointing Control and Aspect Determination System is provided in Reference 18.

The Chandra project team discovered at their Critical Design Review (CDR) that disturbances due to RW imbalance were too large, and determined that the only way to comply with its jitter requirements was to include RW isolation. The passive RW jitter isolation system used to meet the Chandra's imaging performance requirements is described in Reference 19.

The CDR jitter results were a disturbing surprise to the project team since the design margins were healthy until new models for all subsystems were included in the CDR analysis cycle. This experience points to the recognition that inclusion of sufficient uncertainty in analytical predictions is needed to avoid late requirement violations.

Solar Dynamics Observatory (SDO)

The Solar Dynamics Observatory (SDO) spacecraft carries three Sun-observing instruments to geosynchronous orbit: Helioseismic and Magnetic Imager (HMI), the Atmospheric Imaging Assembly (AIA), and the Extreme Ultraviolet Variability Experiment (EVE). The basic mission of SDO is to observe the Sun for a very high percentage of the 5-year mission (10-year goal) with long stretches of uninterrupted solar observations and with constant, high-data-rate transmission to a dedicated ground station. The SDO mission has very tight pointing jitter requirements for its Sun-observing instrument pointing. Both the AIA and HMI science instruments on SDO are sensitive to high-frequency pointing perturbations and have sub-arcsec level LoS jitter requirements. These stringent mission requirements became design drivers for the observatory in general and for the ACS in particular. A detailed description of the SDO's ACS is provided in Reference 20. Each science instrument has an Image Stabilization System (ISS) with some ability to compensate for high frequency motion. Below the bandwidth of the ISS, the control system itself must suppress disturbances within the ACS bandwidth while also avoiding exciting jitter at higher frequencies.

A jitter analysis activity performed early in the SDO project lifecycle for which the objective was to verify requirements using a preliminary observatory structural finite element model (FEM) and preliminary RW disturbance models is described in Reference 21. The results of this early analysis provided the SDO project team a direct comparison of jitter performance using two different candidate RWs. These early results were then employed by project decision makers to technically inform the SDO RW selection process. The results of SDO jitter analysis and modeling efforts are documented in Reference 22.

Another important SDO jitter-related activity was the design of a new pointing algorithm, which mitigated the spacecraft's HGA jitter during the motion of the two HGA antennas during high data rate communications downlink periods. As mentioned above, the SDO's science instruments require fine Sun pointing and have a very low jitter tolerance. Analysis showed that the nominal tracking and slewing motions of the antennas could cause enough jitter to exceed the specific portion of the jitter budget allocated to the HGA disturbance. As described in Reference 23 the HGA pointing control algorithm was expanded from its original form in order to mitigate the jitter.[23]

Since, as mentioned above, both the AIA and HMI science instruments on SDO are very sensitive to the blurring caused by jitter, extensive modeling and analysis was performed at the NASA Goddard Space Flight Center (GSFC). To verify the disturbance models and to validate the jitter performance prior to launch, many jitter-critical components and subassemblies were tested either by the mechanism vendors or by NASA GSFC. Although detailed analysis and assembly-level tests were performed to obtain good jitter predictions, there were still several sources of uncertainties in the system. The structural FEM did not have all the modes correlated to test data at high frequencies (>50 Hz). The performance of the instrument stabilization system was not known exactly but was expected to be close to the analytical model. A decision was made that a true disturbance-to-LoS observatory-level test would not be performed for multiple reasons: schedule impact, cost, technical challenges in implementing an effective 1-g negation system from which to suspend the SDO spacecraft, and the attendant risks of potentially damaging flight hardware. To protect the observatory jitter performance against model uncertainties, the SDO jitter team devised several on-orbit jitter reduction plans in addition to specifying reserve margins on analysis results. Since some of these plans severely restricted the capabilities of several spacecraft components (e.g., the RWs and HGA), the SDO team performed on-orbit jitter tests to determine which jitter reduction plans, if any, were necessary to implement in order to satisfy science LoS jitter requirements. The SDO on-orbit jitter tests described in Reference 24 were constructed to satisfy the following four objectives: 1) determine the acceptable RW operational speed range during Science Mode, 2) determine HGA algorithm jitter parameters, 3) determine acceptable spin rates for EVE instrument filter wheels, and 4) determine if AIA instrument filter wheels excite the first AIA telescope structural mode.[24]

Solar and Heliospheric Observatory (SOHO)

The Solar and Heliospheric Observatory (SOHO) spacecraft, a cooperative effort between the European Space Agency (ESA) and NASA, was launched in December 1995 into a halo orbit around the Lagrange Point L1 of the Sun-Earth System. Originally planned as a 2-year mission, SOHO continues to operate today after over 20 years in space and, in November 2016, an extension lasting until December 2018 was approved by mission managers. The SOHO spacecraft was designed to provide the science instruments with LoS stability below their image pixel or resolution requirements. This translated into short-term stability requirements below 1 arcsec for most of the instruments in the payload. The performance objective was to keep the peak dynamic jitter as low as 0.3 to 0.5 arcsec. The jitter problem thus presented to the SOHO team was a challenging one. This was especially true given the limited state in-house experience and knowledge base in the early-mid 1990s for dealing with such a complex observatory. The SOHO jitter assessment study, as described in detail in Reference 25, was formulated as a well-balanced, pragmatic, and logical combination of analysis and multiple tests to anchor the models and jitter prediction simulations.[25] A series of modal survey tests on observatory substructures was performed to support the construction of a validated spacecraft structural FEM. Component-level testing was performed to characterize the individual disturbance sources. The most significant disturbances were identified as the RWs, which are very typical, as well as a number of scanning, focusing, and rolling mechanisms associated with individual science instruments. A SOHO jitter prediction analysis was performed, which supported the project team in the process of working out the appropriate pointing/jitter error budget and proper requirements flow down. A final pre-launch jitter verification DIT test was performed in February 1995 on a representative configuration of the flight model SOHO spacecraft. Similar to most such full-up observatory DITs, the fundamental objective of this test was to make experimental measurements of the jitter induced on the most sensitive instruments by sequential activation of individual "real-world" disturbance sources. The SOHO jitter team was especially interested in obtaining this LoS jitter data at frequencies above 150 Hz, the frequency point beyond which the validity of the spacecraft FEM was believed by the team to be questionable. The SOHO spacecraft was hung in the test facility using a compliant bungee-cord-like suspension system to minimize gravity effects towards the goal of replicating the free-free boundary conditions found in-flight. The jitter test data collected during this suspended DIT correlated well with the analytical predictions with any deviations being explainable. It is noteworthy that the DIT data revealed that the jitter level induced on the payload instruments above 150 Hz was very small for all of the disturbance sources.

As related in Reference 24, the ultimate validation of acceptable in-flight jitter levels was accomplished through the use of a clever jitter measurement technique. The ISS of SOHO's Michelson Doppler Imager (MDI) contains a relatively high bandwidth electro-mechanical servo-actuator for performing active closed-loop LoS stabilization using a small gimbaled mirror, which is tilted by an angular actuator. SOHO's downlinked telemetry includes a measurement of the servo-actuator current, which is sampled at a 512-Hz rate. Essentially this measurement of this ISS servo current, converted to an angular representation with a threshold of a few tenths of a micro-radian, provides a direct indication of the jitter amplitude as measured at the MDI instrument LoS level. Systematic calibration of the MDI ISS servo signal was done pre-launch during SOHO jitter ground testing and the capability to make these jitter measured was demonstrated in the ground test environment as well. There are limitations on this technique of using the MDI ISS for in-flight jitter measurements, however. For example, LoS jitter is measured in-flight only on the MDI, and furthermore it is measured only at some selected RW speeds. As indicated in Reference 24, it is not possible to acquire and downlink the MDI ISS data during a RW spin down. Comparing the in-flight jitter data with pre-launch analytical jitter predictions and with ground test results showed a general positive consistency in the jitter levels. However, in some instruments the in-flight LoS jitter was seen to be much less than predicted by the jitter analysis. Investigations into those discrepancies revealed the cause of the over-predictions to be either the use of worst-case analytical assumptions not actually seen in-flight or less dynamic coupling than assumed in the pre-launch jitter analysis.

Looking back, the SOHO jitter assessment experience appears to have been a very comprehensive and well-constructed campaign from which both ESA and NASA drew some important lessons learned to apply to their future complex and demanding mission applications. This SOHO experience points to the importance of understanding the observatory's disturbance spectrum (from various sources) and its impact on critical payload elements. Understanding what the effects are on pointing stability and determining if any local payload structure get excited by the disturbances is sometimes only revealed by testing. The spacecraft FEM will usually provide the jitter team with clues with respect to susceptible frequencies, but there is significant uncertainty in how energy is actually attenuated and spread across a given structure. Much of this uncertainty comes from a lack of knowledge concerning energy transmission across structural interfaces and devices such as joints, hinges, and brackets. A physical observatory system-level test to assess dynamic interactions, in which disturbance sources are operated and resulting LoS performance is measured, is an indispensable way to increase the pre-launch understanding of the complex dynamic interactions taking place within the observatory. A comprehensive DIT should be performed over all frequencies of interest, not just those with where the spacecraft FEM is expected to be less valid.

One last comment on the SOHO experience concerns their comparison of pre-launch analytical jitter predictions with the observed in-flight jitter. One would expect that, and in fact should ensure that, the pre-launch analysis is always conservative (e.g., accomplished through the use of conservatively low values of damping and/or the use of more compliant coupling terms) and that the actual in-flight performance should be better than predicted, which is what was experienced on SOHO as described above. However, one must protect against weaknesses in the overall conservative nature of the pre-launch analysis. For example, the analysis may not properly account for observatory structural modes being excited, particularly by high-frequency harmonic content (tones) of the various disturbance sources. All of this points towards the need for rigorous pre-launch DIT campaign.

James Webb Space Telescope (JWST)

On the James Webb Space Telescope (JWST) science observatory, the ACS provides attitude determination and control for all mission phases and modes of the observatory. JWST uses six RWs to generate control torques to orient the observatory with ACS sensing functions performed by three star trackers and six gyroscopes. This enables coarse pointing sufficient to keep the SA pointed at the Sun and the high-gain antenna pointed at the Earth. To take images and spectra of astronomical targets, finer pointing is needed. The ACS therefore interfaces with the Fine Guidance Sensor (FGS), located in the Integrated Science Instrument Module (ISIM), and with the telescope's fine steering mirror (FSM) for fine pointing control during observations. JWST's requirement for telescope LoS motion is <3.7 mas. As described in Reference 25, a two-stage passive vibration isolation system will be used on JWST to attenuate higher frequency (>2.0 Hz) jitter disturbances associated with RW static and dynamic imbalances,[25] as well as bearing run-out.[26] The JWST Stage 1 isolation consists of 7.0-Hz RW isolators located between each RW and the spacecraft bus, while the Stage 2 device is a 1.0-Hz tower isolator between the spacecraft bus and the observatory's Optical Telescope Element (OTE). The RWs are speed biased to 2700 rpm by using an additional bias control loop that regulates RW speed operation near a fixed speed in the null-space of the RW cluster. This RW speed bias set point is needed to maintain RW speeds within an acceptable speed range of 15 Hz to 75 Hz in order to avoid exciting structural vibrations that may contribute to LoS jitter.

Geostationary Operational Environmental Satellite (GOES)

GOES-16, previously known as GOES-R, is the first of the next generation GOES-R series of GOES operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). The GOES-R series program is a collaborative effort between NOAA and NASA. These advanced meteorological spacecraft were designed and built by Lockheed Martin and their acquisition technically and programmatically managed by NASA GSFC in Greenbelt, Maryland. GOES-16 was launched on 19 November 2016 and, as described in Reference 27 it represents a dramatic performance leap in Earth and solar weather observation capabilities.[27] However with the improved metrological payload resolution comes the instrument suite's increased sensitivity to jitter disturbances over the broad frequency range of 0-512 Hz. Disturbance sources include RWs, thruster firings for station keeping and momentum management, gimbal motion, and internal instrument disturbances. To minimize the impact of these disturbances, the baseline GOES-R design includes an Earth Pointed Platform (EPP), which is a stiff optical bench on which the two nadir pointed instruments are collocated together alongside the GN&C subsystem's 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 approximately 5 Hz in all six Degrees-of-Freedom (DOF).[28] A switch in RW vendors occurred late in the development of GOES-R program. To reduce the risk of RW disturbances impacting performance, a secondary passive isolation system manufactured by Moog CSA Engineering was incorporated under each of the six 160 Newton-meter-second (Nms) RWs. This secondary passive isolation system was specifically tuned to provide attenuation at frequencies above approximately 50 Hz. Integrated wheel and isolator testing was performed on a Kistler table at NASA GSFC. High-fidelity simulations were conducted to evaluate jitter performance for four topologies: 1) hard mounted no isolation, 2) EPP isolation only, 2) RW isolation only, and 4) dual isolation. The pre-launch simulation results, as reported in Reference 29, demonstrated excellent performance relative to the GOES-R pointing stability requirements, with dual isolated LoS jitter predictions being less than 1 micro-radian.[29] A comparison of pre-launch to post-launch GOES-16 satellite dynamic interaction characterization results is documented in Reference 30. In particular, the GOES-16 post-launch on-orbit dual isolation performance characterization test results indicate in-flight dynamic behaviors in general agreement with pre-launch analytical predictions.[30] Reference 31 provides an up-to-date examination and comparison of the in-flight LoS pointing performance seen on the GOES-16 and GOES-17 spacecraft.[31]

In addition, Reference 32 provides a thoughtful and informative retrospective look back at the early work performed to develop the original GOES Image Navigation and Registration (INR) system. This reference examines the dynamic interactions and jitter experienced on the GOES I-M series of spacecraft and documents key lessons learned from those ground-breaking engineering solutions to the LoS jitter problem.[32]

Wide Field Infrared Survey Telescope (WFIRST)

Scheduled to launch in the mid-2020s, the proposed Wide Field Infrared Survey Telescope (WFIRST) would have 300 megapixel Wide Field Instrument that images a sky area 100 times larger than HST. Given the demanding jitter challenges and multi-disciplinary nature of the problem there is extensive use of Integrated Modeling (IM) and integrated performance analysis on WFIRST as was done on JWST.[33]

In addition to its Wide Field Instrument, the baseline design of WFIRST also features a coronagraph technology demonstration instrument designed to directly image exoplanets by blocking out a star's light, allowing the much fainter planets to be observed. As NASA's first advanced coronagraph in space, it would be 1,000 times more capable than any previously flown. Internally the WFIRST CoronaGraph Instrument (WFIRST-CGI) includes both a Shaped Pupil Coronagraph (SPC) and a Hybrid Lyot Coronagraph (HLC). This WFIRST-CGI requires unprecedented levels of stability over multiple hours (5 to 100) of observations, while requiring these levels of stability to be repeatable in a Root Mean Squared (RMS) sense from observation to observation. The level of pointing stability required is 0.7 mas RMS per axis per observation and has to be repeatable at the 0.5 mas RMS level from observation to observation. In addition to stability, the pointing system bias must also be repeatable at the 0.1-mas level between observations. These pointing requirements are paramount to maintaining the needed raw contrast levels between the intensity level of the star of interest and the level of obscuration achieved by the two internal coronagraphs. To meet these requirements, the WFIRST-CGI team takes advantage of the spacecraft's ACS (a 8-mas 1-sigma/axis class pointing system) and passive jitter designs (12-mas 1-sigma/axis class passive jitter design driven by the dual isolated RWs) already planned for WFIRST while constraining the RW speeds to regimes favorable to the control system bandwidth in CGI (30 Hz). While the CGI design is currently meeting its requirements, this could easily change between SRR (the current project phase) and Launch, as the IM team matures its design and models. So, to allow maximum design freedom to the IM team, the exported jitter requirement flowed down to them contains the CGI team's closed loop rejection function to allow quick assessment of exported jitter to CGI after the CGI control system is used.

Space Interferometry Mission (SIM)

The Space Interferometry Mission (SIM) science goals were to provide direct measurements of the wobble of stars due to orbiting planets, while doing wide and narrow angle astrometry, and generating a star-catalog that will be orders of magnitude better than the Hipparcos catalog. The proposed SIM payload included three stellar interferometers, each with a baseline of 10 meters, and an interferometric baseline vector defined by each of the interferometers' pair of primary mirrors. Of the three interferometers, only one was used for science data collection, while the other two were used to accurately measure the changes in attitude of the science interferometer's baseline attitude in space. SIM used a network of metrology beams (external metrology) to transfer the attitude measurements made with the guide interferometers to the science interferometer's baseline attitude. The SIM project made considerable investments in the development of interferometer metrology technology.[34] The requirement on relative attitude knowledge obtained by each interferometer over all time scales up to 1 hour was 0.2 mas RMS. To meet this requirement SIM had to form and track starlight fringe position for each of its interferometers to less than 10 nanometers RMS for observations as long as 1 hour. This level of performance was accomplished using a multi-disciplinary approach that combined the ACS, the structure, the instrument stability, and the instrument's own fringe tracking system, which included a complex network of metrology systems. Some key aspects of the design were: 1) a 2-arcsec class spacecraft ACS for rigid body motion pointing control, 2) a precision support structure that minimized thermal distortion and response to jitter sources, 3) a dual stage isolation system for the 6 RWs on the spacecraft, 4) use of precision optical mounts and mechanisms that minimize their susceptibility to disturbance while also minimizing their generation of jitter, 5) external metrology to relate attitude from the guide baselines to the unmeasured attitude of the science baseline, 6) internal metrology to measure the changes in optical path traveled by the starlight on both arms of each interferometer, 7) a fast steering mirror to compensate for each telescope's aperture pointing error to the tune of 30 mas

RMS (two per interferometer), and 8) a three-stage active mechanism for each interferometer to compensate for all residual fringe tracking errors.

Given the unprecedented level of stability required, it was clear from the beginning that modeling uncertainty was going to be an issue for SIM. How much uncertainty is there in model-based predictions? Is the uncertainty in modeling under predicting or over-predicting performance? If predictions are scaled by some agreed upon level of uncertainty in models, and requirements are broken, should the project spend budget and resources to attack design deficiencies? At what point in the design cycle should the project react to these results?

The SIM project built a full-scale testbed version of the flight system, called the STB3, which included the instrument, spacecraft, dual isolation system, and a pseudo star for a "test as you fly" style technology demonstration and modeling verification.[35,36,37] The idea was to demonstrate directly the feasibility of achieving the stability and knowledge requirements discussed above. An additional benefit of building STB3, was that we could compute the prediction error of our models vs. actual measurements of instrument performance out to 1 KHz, which would give us a realistic notion of uncertainty. These comparisons were made for three levels of model fidelity consistent with common modeling practices at Preliminary Design Review (PDR), CDR and post Integration and Test (i.e., after model correlation is concluded).

Figure 4 shows the uncertainty functions based on the ratio of measured performance to model predictions in STB3. Some level of smoothing was used to allow easy adoption by the flight system. In all cases, models under-predicted testing, and the predictions got better as model fidelity increased. While this was expected, the real value of this work was to provide a sense of scale for the uncertainty. Along with these functions goes the assumption that flexible body dynamics damping is equal to 0.25% for all modes in the models, and that the first flexible body frequency is above 10 Hz (excluding the isolation system, which had modes between 2 and 7 Hz). A key point to note is that even after test-to-model correlation work was done, the predictions continued to under-predict the measurement. The functions in Figure 4 were adopted by the Jet Propulsion Laboratory (JPL) Dynamics and Controls team to appropriately scale their raw predictions and to recommend SIM design changes as needed, so that at PDR, CDR, and post testing during the integration and test phase the flight system could always show positive margins against requirements.

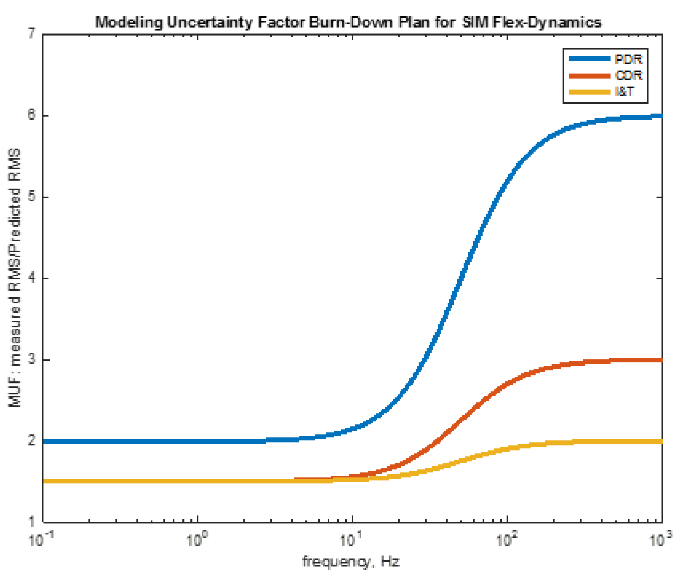

Figure 4. SIM Flight System Modeling Uncertainty Factors for Flexible Dynamics.

Soil Moisture Passive Active (SMAP)

The Soil Moisture Passive Active (SMAP) synthetic aperture radar pointing system was driven by the need to reconstruct its boresight pointing angle and the need to calibrate the boresight of the Stellar Reference Unit to the boresight of the reflector boresight as it spun at 0.25 Hz. The jitter problem was from the start a non-issue for SMAP given its large boom (6 meters) and large reflector (6 meters in diameter), which acted as isolators with corner frequency at 1.75 Hz while the RWs were biased to operate between 34 and 40 Hz. The wobble of the boom/reflector pair due to mass imbalance (dynamic and static) never interacted with the flexible body dynamics of the instrument or with the SAs (the first SA flexible mode was greater than 3 Hz). The speed control error in the spun instrument assembly never generated disturbances large enough to excite the flex dynamics of the boom/reflector noise to appreciable levels in analysis or in flight. A small but significant surprise in SMAP was the measured damping. The design assumed 0.25% damping to be very conservative, but a direct measurement using the on-board gyro sampled at 200 Hz yielded an in-flight value of only 0.15% for the reflector first mode, which was previously outside of the JPL experience base. Note that the reflector mode with this level of damping was primarily straining the small prime-batten metal boom connecting the reflector to the rest of the large 6-meter boom. No room for anything other than pure material damping should be expected in this case.

SOME SPACECRAFT LOS JITTER LESSONS LEARNED AND RULES OF THUMB

As alluded to above, the jitter challenge consists of protecting against degraded output performance of the payload's optical sensors caused by the transmission of spacecraft internal mechanical disturbances from their source through the vehicle's structure to the sensing elements in the payload instruments. These optical degradations typically occur due to high-frequency (relative to the spacecraft's attitude control bandwidth), low-energy excitations of the spacecraft system's structural modes of vibration that often possess very low inherent damping. For the majority of NASA's science missions, the jitter problem solution is focused on the modeling, analysis, and test of precision optical-mechanical space observatory systems (i.e., a spacecraft bus supporting a science instrument payload) but jitter can also impact precision pointing of steerable HGAs. Depending on the nature of the "transfer function" of a given space vehicle configuration (i.e., the structural input/output model between a disturbance input node and the payload sensor output node of interest) the spacecraft structure will either amplify or attenuate that particular disturbance. The structure's resonant frequencies, the damping level in the system and significant system non-linearities are the key parameters influencing this amplification/attenuation dynamic behavior. The level of structural mode damping assumed in the system model will have a great influence on the level of jitter seen at the structural resonance frequencies. In spacecraft jitter analyses, it is not uncommon to use values in the range of 0.5% to 0.25% damping (uniformly applied to all vibration modes) resulting in dramatically high resonance amplification factors (i.e., Q) in the 100-200 range at the resonant modes of the spacecraft structure. The SDO experience revealed that a damping ratio of 0.3% was a good value for jitter analysis for a conventional structural system at a typical (non-cryogenic) temperature range.[24] In certain relatively rare jitter studies, the damping values used could potentially be in the lower range of 0.1% to 0.25%. Recall that on SMAP, as mentioned above, JPL engineers directly measured an in-flight damping of only 0.15% for the reflector first mode.

In the view of the authors, there is a general lack within the spacecraft engineering community of well-established and published engineering guidelines defining uniform practices for the process of assessing, controlling, and managing observatory jitter. For example, at NASA there currently is no existing Agency-level set of established best practices for performing observatory jitter analysis. This is not to say that several of the spacecraft engineering originations at the NASA Centers do not have their own in-house best practices for performing observatory-level jitter analysis. The degree to which these are documented and shared across the Agency is very limited however.

Documenting these best practices for performing observatory-level modeling, simulation, analysis, and test activities associated with solving the spacecraft jitter problem is a goal of the NASA Engineering and Safety Center (NESC) GN&C Technical Discipline Team (TDT). The NESC GN&C TDT is chartered to perform such GN&C discipline knowledge capture work in support of NASA's goals for retaining and sharing Agency-wide, highly specialized engineering 'tribal knowledge'. In addition, the NESC GN&C

TDT is interested in capturing relevant lessons learned from past missions that have dealt with the spacecraft jitter problem, successfully or otherwise. Later on in this paper, some specific and relevant jitter lessons learned will be presented.

Before leaving this discussion of jitter engineering knowledge capture, the authors would like to single out one very significant contribution, in their view, to the community's common knowledge base for approaching and solving the spacecraft jitter problem. Readers are encouraged to refer to Section 13.3, entitled "Jitter." of the Spacecraft Mechanical Loads Analysis document (ECSS-E-HB-32-26) that has been prepared and publically released by the European Space Agency/European Cooperation for Space Standardization (ESA/ECSS) organization.[1] This document provides an excellent resource for engineers covering the general aspects of the spacecraft jitter problem, and also presents some detailed information on jitter analysis, modeling requirements, LoS budgeting assessment and pointing error synthesis, and a discussion on jitter verification testing.

A technically sound spacecraft jitter effort consists of both analytical work and focused testing. As described above fundamentally jitter can cause undesired distortions on the payload instrument's sensitive optical axis LoS pointing. Although individual programs/projects may have mission-unique definitions of "LoS jitter" one can in general consider this to be undesired motion of a payload's sensor optical boresight axis over the duration of the sensor's focal plane integration time. The sensor's focal plane integration time(s) is a key parameter in any assessment of LoS jitter in that it determines the frequency range(s) of critical interest for mitigating the unwanted effects of jitter.

Within the broad aerospace community, the importance and value of identifying, documenting, and widely sharing lessons learned is now broadly acknowledged. However, significant lessons learned on a project often are not captured even though they are well known, highly specialized, 'tribal knowledge' amongst the project team members. Documenting and sharing lessons learned helps engineers and managers to minimize project risk and improve performance of their systems. In the authors' view, leveraging lessons learned is especially valuable on new system development projects to help overcome the team's unfamiliarity with previously identified technical pitfalls and challenges.

It is in that spirit that we informally offer the following lessons learned from our experiences working spacecraft jitter problems:

1. Jitter can affect any design, but the impacts are not all the same.
2. Just because jitter requirements are easy or nonexistent for a given design, it does not mean they won't play a role in performance.
3. When jitter-related requirements are challenging, iterating on system architectures with adequate model fidelity is paramount to selecting the right architecture.
4. The more challenging a jitter-related set of requirements, the higher the need for model fidelity at the start of a project.
5. There is no substitute for early sensitivity analysis especially as part of a complete error budgeting.
6. A complete error budget is absolutely needed at the start of a project that has challenging jitter requirements.
7. It is paramount to identify all possible sources of error early in the design cycle. Do this even if quantification is not easy or their effect is perceived to be inconsequential.
8. Jitter is a system-level problem. This is one case where truly all aspects of a system design strongly couple and challenge the typical subsystem design. The tougher the requirement the stronger the inter-subsystem dependencies and the harder it is to solve the problem within the domain of a single subsystem. In the limit, the toughest jitter problems require a system level team that encompasses all subsystems. JPL calls this team the Dynamics and Controls team, separate from the GN&C, Mechanical, /Instrument, Navigation, and Ground teams.
9. The more challenging jitter problems require larger and more technical teams. Project management should therefore plan and budget appropriately the necessary team resources.
10. The team tackling the jitter-related requirements works best when it can clearly decompose the design job among the classical subsystems in a project, while taking on the task of validating this decomposi-

tion and owning the observatory's jitter-related requirements Verification and Validation (V&V). This team must make sure it can model the nuances that will inevitably come with this decomposition.

11. The team tackling the jitter must start its work early in the project design cycle and must endeavor to understand the nuances of the decomposition of its work into individual subsystem requirements as early as possible. However, as the system design progresses it is quite likely that new requirements on the subsystems will be needed to deal with the nuances discussed above.
12. The team working on the jitter-related requirements for the project will very likely drive the system level design, architecture, testing and thus the project cost/schedule, hence it must be prepared to constantly communicate its results, solutions, strategies, and architecture to get the project, system and subsystem's buy-in on them. Communication is very important to ensure all the subsystems are working together to meet the jitter team's requirements.
13. Jitter will couple the spacecraft subsystems; however, this is not a license to come up with complex designs. It is always best to keep the solutions simple even if that means over-achieving. Operational simplicity and flight heritage must always be kept in mind.
14. Keep the on-board calibrations and alignments for challenging jitter problems in front of the jitter team to ensure the errors and nuances associated with these errors are not omitted until it is too late.
15. Incremental piecewise testing to inform and anchor the model, reducing system performance risk, is critically important for many missions.
16. A solid observatory system-level jitter test is the best way to gain confidence in an End-to-End model and performance predictions, and tests can be valuable for a range of configurations, some with minimal impact to existing observatory test plans.
17. Design the observatory system to be flexible and "tunable" in the event of unforeseen dynamic interaction problems appearing in-flight. Flexibility with disturbance sources (e.g., cryocoolers, SA and/or HGA drive mechanisms, etc.) can be achieved with a range of selectable discrete drive frequencies or other operational scenarios (e.g., randomized stepping of drives) to avoid problematic frequencies. Likewise, provisions to apply operational constraints (e.g., reaction wheel speed stay out zones) can prove useful. In order to gather information and gain insights consider including sensitive instrumentation (e.g., accelerometers) on the bus and the payload to understand in-flight dynamic behaviors. Lastly, employing data from individual mechanism feedback sensors and/or drive signals (e.g., an instrument scanner servo error) could also yield performance insights and should assist engineers in understanding the nuances of in-flight LoS pointing. However, one must ensure these informative signals can be collected at sample rates (using telemetry dwell capability) that allow the requisite bandwidth for useful analysis on the ground.

In summary, the big picture jitter design guidance to be extracted from all the above lessons learned would be along the lines of the following:

- ✓ Architect the observatory system very carefully early on in the life cycle
- ✓ Understand all the system sensitivities
- ✓ Build and authorize the jitter team
- ✓ Analyze and test systematically
- ✓ Have multiple "knobs" one can turn for in-flight system adjustments

The most important message the authors wish to convey to the reader is the imperative of focusing on and making critical architectural decisions early on in the process. Architectural decisions made early in a project's lifecycle always have long-term mission consequences and ramifications. It is not an overstatement to point out that, more often than not, mission success will depend on the quality of the observatory-level architectural decisions that are made in the early stages (e.g., the Formulation Phase) of a project lifecycle. In order to make the 'best' (i.e., the most-informed) architectural decisions both a comprehensive process and an associated multi-disciplinary jitter team organization needs to be established early on.

Table 1 summarizes, in a concise and compact format, the 'rules of thumb' described above. Table 1 illustrates which jitter designs are already known, which design drive the overall system, which designs represent the state of the art, and, lastly, which designs pose development risk as they are beyond the current state of the art.

Table 1. Rules of Thumb for Initiating and Approaching New Jitter Designs.

Case	Stability/ Accuracy/ Reconstruction (arc-seconds, 1-σ)	Keys/Drivers to Micro-Vibration Design					
		Architecture	Model/ Simulation	ACS	Structural	Instrument Control	Testing
1	100 ++	ACS	Low Fidelity	HW	Low Freq modal	Functional	Interfaces @ I&T
2	10 → 100	Thermal & ACS	Low Freq & Fidelity	HW, CSI	Mid Freq Modal	Functional	Subsystem V&V @ I&T
3	0.1 → 10	Thermal, ACS & Jitter	Med. Freq & Fidelity, @ PDR	HW, CSI	Mid Freq Modal + Asymptotes	Functional + Compensation	Subsystem V&V @ I&T
4	0.01 → 0.1	Thermal, ACS & Jitter	High Freq & Fidelity @ PDR	HW, CSI Operational	High Freq Modal + Asymptotes	Functional + Compensation	Subsystem @ I&T, Component @ CDR
5	$1e^{-3} \rightarrow 1e^{-2}$	Calibration Thermal, ACS & Jitter	High Freq & Fidelity @ SRR	HW, CSI, Operational, algorithms	High Freq Modal + Tailoring	Functional + distributed Control	System @ I&T, Subsystem @ CDR
6	$1e^{-4} \rightarrow 1e^{-3}$	Calibration Thermal, ACS & Jitter	High Freq & Fidelity @ SRR	HW, CSI Operational, algorithms	High Freq Modal + Tailoring	Functional + distributed Control	System @ I&T, Subsystem @ CDR

Known Designs | Drives System | State of the Art | Beyond State of the art → Risk

Readers seeking additional insights and other rules of thumb regarding preferred ways to manage the observatory LoS jitter, are directed to Reference 38, which is an informative tutorial presentation created by the Aerospace Corporation, under the sponsorship of the NESC GN&C TDT.

CONCLUSION

Looking forward one can identify the clear trends within both NASA towards planning technically aggressive spaceflight missions that include ultra-performance optical payloads with delicate highly vibration-sensitive scientific/observational instruments. For example, extremely formidable and challenging jitter engineering problems lie ahead for NASA in the near-term in the form of WFIRST-CGI and, further down the road, for the potential HabEx and LUVOIR missions. One can foresee that multiple jitter engineering and technology risk areas will obviously need to be mitigated.

To successfully meet these future challenges NASA will need to leverage and build upon their collective past experiences in addressing jitter problems. Looking back one sees that NASA, together with our industry partners, have a long, technically rich, and impressive history of solving the difficult engineering problems associated with managing, controlling, and testing spacecraft jitter. Our experiences in dealing with undesirable jitter perturbing payload instrument pointing/pointing stability have taught us the imperative of focusing on and making critical architectural decisions early on in the process.

When jitter-related requirements are challenging, iterating on system architectures with adequate model fidelity is paramount in the overall process of judiciously selecting the right observatory architecture. Architectural decisions concerning jitter made early in a project's lifecycle, and the decisions not made as well, always have long-term mission consequences and ramifications, both good and bad. The multi-disciplinary jitter team tackling the jitter problem must start its work early in the project design cycle and must endeavor to understand the nuances of its work decomposing observatory-level requirements into subsystem requirements as early as possible.

In this paper, the authors have attempted to share their subject matter knowledge and their perspectives on the spacecraft LoS jitter problem. It was pointed out that before starting the design process a jitter analyst should recognize and understand that not all observatory designs require the same level of care and attention when it comes to solving the jitter problem. The design process is of course iterative, but one must start a new design somewhere. The authors provided some of their recommended rules of thumb to provide some guidance on where to initiate and how to approach a new jitter design challenge. The authors also presented a set of jitter lessons learned that we believe are valuable, worth sharing with the community, and which can be leveraged on new system development projects to help overcome the team's unfamiliarity with previously identified jitter technical pitfalls and challenges.

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REFERENCES

[1] European Space Agency, European Cooperation for Space Standardization (ESA ECSS) (2012), Section 13.3 Jitter, Space Engineering: Spacecraft Mechanical Loads Analysis Handbook, ECSS-E-HB-32-26.

[2] Addari, D., (2016), A Semi-Empirical Approach for the Modelling and Analysis of Microvibration Sources On-Board Spacecraft, Chapter 2, PhD Thesis, University of Surrey.

[3] Kamiya, T., et. al. (2004), Microvibration Management and Pointing Stability Analysis of SELENE Satellite, *IFAC Automatic Control in Aerospace*, Saint-Petersburg, Russia.

[4] Yoshida, N., et al. (2013), Spacecraft with Very High Pointing Stability: Experiences and Lessons Learned, *IFAC Proceedings* Volume 46, Issue 19, 2013, Pages 547-552, 19th IFAC Symposium on Automatic Control in Aerospace, 2-6 September 2013, Würzburg, Germany.

[5] Dennehy, C. and Alvarez-Salazar O. S., (2018), "Spacecraft Micro-Vibration: A Survey of Problems, Experiences, Potential Solutions, and Some Lessons Learned," *European Conference on Spacecraft Structures, Materials & Environmental Testing (ECSSMET2018)*, 28 May - 1 June 2018, ESA/ESTEC, Noorwijk, The Netherlands.

[6] Dougherty, H. J., et. al. (1982), Space Telescope Pointing System, *Journal of Guidance, Control, and Dynamics*, Vol. 5, No. 4, 1982, pp. 403-409

[7] Dougherty, H. J., Rodoni, C., Rodden, J., & Tompetrini, K. (1983), Space Telescope Pointing Control", AAS/AIAA Paper 83-365, *Astrodynamics*, Volume 54 1 & 11, Advances In The Aeronautical Sciences, 1983.

[8] Nurre, G. S. & Dougherty, H. J. (1984), *The Pointing System for Space Telescope, The National Symposium and Workshop on Optical Platforms*, Charles L. Wyman, editor, Proceedings of SPIE, vol. 493, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA.

[9] Beals, G. A., et. al. (1986), Space Telescope Precision Pointing Control System, AIAA Technical Paper 86-1981, *AIAA Guidance, Navigation, and Control Conference Proceedings*.

[10] Hasha, M. D. (2016), High-Performance Reaction Wheel Optimization for Fine-Pointing Space Platforms: Minimizing Induced Vibration Effects on Jitter Performance plus Lessons Learned from Hubble Space Telescope for Current and Future Spacecraft Applications, *Proceedings of the 43rd Aerospace Mechanisms Symposium*, NASA Ames Research Center, 4-6 May 2016.

[11] Nurre, G. S., Sharkey, J. P., & Waites, H. B. (1991), Initial Performance Improvement Due to Design Modifications for the Pointing Control System on the Hubble Space Telescope, *AAS Paper 91-071*, *Proceedings of the 14th Annual American Astronomical Society (AAS) Guidance and Control Conference*, Keystone, CO, February 1991.

[12] Vadlamudi, N., Blair, M. A., & Clapp, B. R. (1992), Hubble Space Telescope On-Orbit Transfer Function Test, AIAA Paper 92-4614, *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Hilton Head Island, South Carolina, United States, August 1992.

[13] Sharkey, J. P., Nurre, G. S., Beals, G. A., & Nelson, J. D. (1992), A Chronology of the On-Orbit Pointing Control System Changes on the Hubble Space Telescope and Associated Pointing Improvements, *AIAA Paper 92-4618, AIAA Guidance, Navigation and Control Conference*, 10-12 August 1992, Hilton Head Island, South Carolina, United States.

[14] Nurre, G. S., et. al. (1993), Design and Performance of the Currently Flying HST Pointing Control System, *AAS Paper 93-002, Proceedings of the 16th Annual AAS Guidance and Control Conference*, Keystone, CO, February 1993.

[15] C. L. Foster, Tinker, M. L., Nurre, G. S., & Till, W. A. (1995), *The Solar Array-Induced Disturbance of the Hubble Space Telescope Pointing System*, NASA TP-3556, May 1995.

[16] Jedrich, N., et. al. (2002), Cryo Cooler Induced Micro Vibration Disturbances to Hubble Space Telescope, *SPIE* (NASA Tech Doc N20020060462).

[17] Clapp, B. R., Sills, J. W., & Voorhees, C. (2002), Hubble Space Telescope Pointing Performance Due to Micro-Dynamic Disturbances from the NICMOS Cyrogenic Cooler, AIAA 2002-1249, *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 22-25 April 2002, Denver, Colorado, United States.

[18] Schauwecker, C J., et. al. (1997), Imaging Pointing Control and Aspect Determination System for the NASA Advanced X-Ray Astrophysics Facility, *Proceedings of the Annual AAS Rocky Mountain Guidance and Control Conference*, AAS 97-04, pp. 233-249, 1997.

[19] Pendergast, K. J., & Schauwecker, C. J. (1998), Use of a Passive Reaction Wheel Jitter Isolation System to Meet the Advanced X-Ray Astrophysics Facility Imaging Performance Requirements, NASA CR-1998-207926, *Astronomical Telescope and Instrumentation Conference, International Society for Optical Engineering*, 20-28 March 1998; Kona, Hawaii, United States.

[20] Starin, S. R., et al. (2005), Attitude Control System Design for the Solar Dynamics Observatory, NASA/GSFC Code 595 F*light Mechanics Symposium*, 18-20 October 2005, Greenbelt, Maryland, United States.

[21] Liu, Kuo-Chia, & Andrews, S. (2003), SDO Jitter Analysis Approach, NASA/GSFC/Code 595 Briefing, 21 August 2003, https://femci.gsfc.nasa.gov/presentations/Liu_JitterAnalysisApproach.pdf.

[22] Liu, Kuo-Chia, et al. (2005), Dynamic Jitter Modeling and Analysis of Solar Dynamic Observatory, *Flight Mechanics Symposium*, NASA Goddard Space Flight Center, Greenbelt, Maryland, United States, October2005.

[23] Bourkland, K. L., Liu, Kuo-Chia, & Blaurock, C. (2007) A Jitter-Mitigating High Gain Antenna Pointing Algorithm for the Solar Dynamics Observatory, *Proceedings of the 20th International Symposium on Space Flight Dynamics*, (NASA/CP-2007-214158), September 2007, Greenbelt, Maryland, United States.

[24] Liu, Kuo-Chia, et al. (2007), Jitter Test Program and On-Orbit Mitigation Strategies for Solar Dynamic Observatory, *Proceedings of the 20th International Symposium on Space Flight Dynamics*, (NASA/CP-2007-214158), September 2007, Greenbelt, Maryland, United States.

[25] Laurens, P., Decoux, E., & Janvier, M. (1996), SOHO Microvibrations: Analyses, Tests and Flight Results, Proceedings of the 3rd ESA International Conference on Spacecraft Guidance, Navigation and Control Systems, ESA SP-381, 1997, ESA/ ESTEC, Noordwijk, the Netherlands, p.489, 26-29 November 1996.

[26] Meza, Luis, et. al. (2005), Line of Sight Stabilization of James Webb Space Telescope, AAS Paper 05-002, *27th Annual AAS Guidance and Control Conference*, 5-9 February 2005, Breckenridge, Colorado, United States.

[27] Chapel, J., Stancliffe, D., Bevacqua, T., Winkler, S., et al. (2014), Guidance, Navigation, and Control Performance for the GOES-R Spacecraft, *Proceedings of the 9th International ESA Conference on Guidance, Navigation & Control Systems*, June 2014, Porto, Portugal.

[28] Davis, L. P., D.R. Carter, D. R., & Hyde, T. T. (1995), Second-Generation Hybrid D-Strut, *Proceedings SPIE* Vol. 2445, Smart Structures and Materials 1995: Passive Damping, pp. 161-175, May 1995.

[29] Freesland, D., Carter, D., Chapel, J., et al. (2015), GOES-R Dual Isolation, the 3*8th Annual AAS Rocky Mountain Section Guidance and Control Conference*, January 2015.

[30] Carter, D., Clapp, et al. (2017), GOES-16 On-Orbit Dual Isolation Performance Characterization Results, *Proceedings of the 10th International ESA Conference on Guidance, Navigation & Control Systems*, 29 May – 2 June 2017, Salzburg, Austria.

[31] Bevacqua T., J. Chapel, D. Stancliffe, T. Rood, D. Freesland, & A. Krimchansky, "In-Flight Line-of-Sight Pointing Performance for the GOES-16 and GOES-17 Spacecraft," AAS Paper 19-133, *42nd Annual American Astronomical Society (AAS) Guidance and Control Conference*, Breckenridge, CO, 1-6 February 2019.

[32] Sudey J., Hagopian, M., & Dennehy C., "GOES I-M: A Retrospective Look INR and Jitter and Lessons Learned," AAS Paper 19-132, *42nd Annual American Astronomical Society (AAS) Guidance and Control Conference*, Breckenridge, CO, 1-6 February 2019.

[33] Liu, K. & Blaurock, C. (2017), Wide-Field Infrared Survey Telescope (WFIRST) Integrated Modeling, Presentation by GSFC's WFIRST Integrated Modeling Team, *NASA Telescope Stability Workshop*, Boulder, Colorado, United States, 4 October 2017.

[34] Laskin, R. A. (2000), Technology Development for the Space Interferometry Mission (SIM) - Status and Plans, *2001 IEEE Aerospace Conference*, Big Sky, Montana, United States, 10 March 2000.

[35] Alvarez-Salazar, O. S., Renaud, G., & Azizi, A. (2004), Space Interferometry System Testbed-3: Architecture, *IEEE Aerospace Conference*, Big Sky, Montana, United States, 6 March 2004.

[36] Dekens, F. G., Alvarez-Salazar, O. S., Azizi, A., et. al. (2004), Kite: Status of the External Metrology Testbed for SIM, *SPIE Conference on Astronomical Telescopes and Instrumentation*, Glasgow, Scotland, 21-25 June 2004.

[37] Fischer, J., Alvarez-Salazar, O. S., Azizi, A., & Sun, G. (2005), Dim Star Fringe Tracking Demonstration on SIM's System Testbed-3 (STB3), *IEEE Aerospace Conference*, Big Sky, Montana, United States, 4-11 March 2005.

[38] Henderson, G., "Managing Observatory Line-of-Sight Jitter: A Design and Development Process Overview, A Beyond the Textbook Tutorial Presentation," *42nd Annual American Astronomical Society (AAS) Guidance and Control Conference*, Breckenridge, CO, 5 February 2019.