

THE NASA JITTER HANDBOOK DEVELOPMENT ACTIVITY: A MULTIDISCIPLINARY COLLABORATIVE EFFORT

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Spaceflight missions hosting high-performance vibration-sensitive optical sensor payloads with stringent pointing stability requirements are especially challenged in the areas of predicting, managing, controlling, and testing spacecraft line-of-sight (LoS) jitter. The community recognizes that this is a formidable multidisciplinary engineering task. However, while some textbooks and references in the aerospace literature may touch on the subject of jitter, important details of specific flight proven methodologies and techniques used by today’s jitter engineering practitioners are not readily accessible. There is no known engineering reference document with guidelines and best practices for managing and mitigating spacecraft jitter. To fill this knowledge gap the NASA Engineering and Safety Center (NESC) has undertaken the task of developing a NASA Jitter Handbook which would include lessons learned and best practices for design, analysis, and test, along with operational guidelines to mitigate jitter. In this paper the plan for this handbook development will be described along with the envisioned handbook framework, key NASA stakeholders, and potential envisioned jitter engineering case studies. Opportunities exist technical collaboration on this handbook with NASA-external organizations.

INTRODUCTION

Across the spaceflight community of practice jitter engineering is a known engineering challenge area with relatively few practitioners and limited subject matter experts. Exacerbating this situation is the fact that there are no established/documented NASA jitter engineering guidelines available. A key finding from a 2019 NESC-sponsored Spacecraft LoS Jitter Workshop was: There is no generally engineering reference document with guidelines and best practices for managing and mitigating spacecraft jitter. Clearly both government and industry would benefit from such jitter engineering guidelines, not only for design purposes, but also for workforce education by collecting/documenting technical insights on jitter analysis and test methods as well as operational considerations.

Jitter is a niche engineering area with few NASA subject matter experts (SMEs) and no established pipeline for the future. Much of this jitter knowledge is treated as proprietary information across industry and is often closely held by the various spacecraft engineering organizations. However, the belief of the handbook team is that there is much basic jitter engineering ‘tribal

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knowledge’ that can be captured without compromising any organization’s proprietary information.

The Nation Aeronautics and Space Administration (NASA) is planning technically aggressive missions that include high-performance optical payloads with delicate, highly vibration-sensitive scientific instruments. For example, the planned Habitable Worlds Observatory (HWO) is a concept for a mission to identify potentially habitable planets around other stars, closely examining their atmospheres to determine if life could possibly exist. The undoubted challenges of jitter for the HWO mission are one of many motivations for the creation of a NASA Jitter Handbook that will capture design, analysis, test, and operational best practices and guidelines.

The NASA Engineering and Safety Center (NESC) recently received approval to perform a year-long activity to develop a NASA Jitter Handbook which would include lessons learned and best practices for design, analysis, and test, along with operational guidelines to mitigate jitter. The NASA Technical Fellow for GNC has assembled a handbook development team of recognized jitter subject matter experts from across the NASA Enterprise, including support contractors. A senior-level Technical Advisory Group (TAG) has also been formed to provide guidance and insight through periodic reviews of interim handbook products.

HANDBOOK DEVELOPMENT CONSIDERATIONS

At the highest level the handbook will address the questions: What is jitter? When does jitter matter? This will involve examinations of different mission classes/types, their GNC/Pointing System architectures, and their associated pointing stability performance requirements. Beyond this the team envisions a handbook that would equally balance the detailed analysis aspects of jitter and the associated forms of jitter testing, from component-level disturbance characterization testing to full-up system dynamic interaction testing. In addition, one of the primary goals of this initiative is to converge on common jitter engineering terminology, across the multiple disciplines and organizations involved. Converging on and documenting a single set of common terminology that all involved parties in the community—government Agencies, industry partners, and academia—can understand and use will be a major contribution of the handbook.

Other aspects of jitter that the handbook would attempt to address include, but are not limited to: defining units and coordinate systems, identifying preferred practices for performing standard checks of the structural Finite Element Models (FEMs), along with the definition of and recommended application of Model Uncertainty Factors (MUFs). Techniques for specifically identifying the necessary features for developing a structural FEM to be used primarily for jitter analysis, compared to those FEMs required and created for the more commonly performed launch vehicle coupled loads analysis, would be covered. The team also recognizes that documenting the best practices for generating a reduced-order state-space model to be used in jitter analysis from the full-order structural FEM (e.g., frequency cutoff) is an important subject to include in the handbook. Lastly, it should be mentioned that the findings and recommendations from the 2019 NASA-sponsored Spacecraft LoS Jitter Workshop will be leveraged as a starting point for this handbook development.

The handbook development team recognizes that not only will the handbook require multidisciplinary inputs (beyond the boundaries of the GNC discipline) but also would benefit from collaboration with other organizations with jitter experience. Thus, the

intention is to ensure the development of this new NASA Jitter Handbook is a collaborative effort. As such the handbook team is intending to leverage the experience and knowledge of representatives not only from NASA and its support contractors but its industrial partners, independent consultant subject matter experts, members of academia and other governmental organization.

The handbook team envisions timely knowledge transfer from, among other missions, the James Webb Space Telescope's (JWST) unprecedented success in this area. Some of the other missions where the team expects to extract lessons learned and best practices include, but is not limited to, the Roman Space Telescope (RST), the Hubble Space Telescope (HST), the Geostationary Operational Environmental Satellites (GOES), the Joint Polar Satellite System (JPSS), the Solar Dynamics Observatory (SDO). There is a near term opportunity (and some degree of urgency) to capture the knowledge of senior jitter subject matter experts who are near retirement and/or recently retired.

Currently the activity is focused on a NASA-centric unclassified Handbook but open for expanded participation. NASA has no established engineering reference document with guidelines and best practices for managing and mitigating spacecraft jitter.

This NESC discipline-advancing assessment will develop an initial version of the NASA Jitter Handbook: Design, Analysis, Test, and Operational Guidelines informed by several relevant NASA case studies. Lesson learned and jitter engineering best practices will be extracted from these case studies. It is envisioned that several mission-level jitter engineering case studies for missions of different mission performance classes will be developed to serve as the core of the NASA Jitter Handbook. In particular, jitter engineering case studies will be created for:

- Hubble Space Telescope: Pointing Control System (PCS) baseline design, subsequent PCS modification and performance improvements, Individual characterization testing of all active components, component modifications to suppress potential vibration sources, Disturbance isolation, Dynamic Interaction Testing.
- James Webb Space Telescope: quiet wheels, Fine Guidance Sensor system, fast steering mechanism to correct LoS, operational constraint during science, control systems optimization.
- Solar Dynamics Observatory (SDO)/JPSS: arc-min pointing: simple conservative analysis, select good components, iterate models (with FEM improvement, modal test results, component vendor tests), decide if it's needed to run a simple Dynamic Interaction Test, be prepared with operational flexibilities.
- Geostationary Operational Environmental Satellites (GOES): quiet low-disturbance components (wheels), architecture which co-locates pointing sensors and instruments on stiff/isolated bench, active disturbance correction.

Beyond these mission-level case studies it is also desired to have a case study examining the accommodation of an Optical Communications Terminal on a spacecraft. For example, a case study capturing the challenges of accommodating the Orion Artemis II Optical Communications System (O2O) would add a different set of jitter engineering considerations to the handbook.

Potential NASA-external collaborators on the development of this handbook are invited to contribute specific case studies from their spaceflight domains.

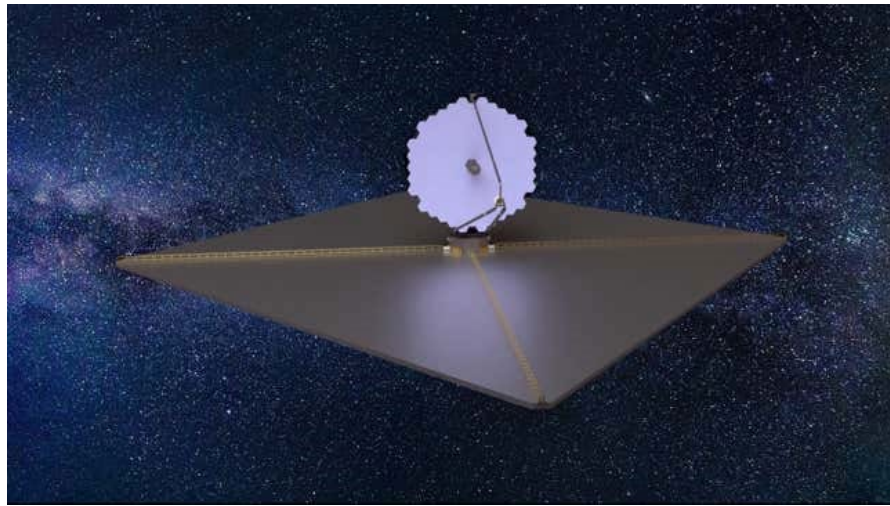
WHY IS JITTER IMPORTANT?

Jitter is a mission-level, multi-discipline system engineering challenge, that, if not appropriately addressed can have significant technical, cost, and schedule impacts for a mission. It is generally the case that for instruments performing precise imaging of celestial targets or the remote sensing of the Earth’s surface, jitter is the key driving requirement for high-quality imaging [1].

In this paper, the term “jitter” refers to un-commanded loss-of-sight (LoS) motion—primarily at frequencies above the spacecraft attitude control bandwidth—that negatively affects image quality. This is distinct from disturbances at relatively lower frequencies, such as thermo-elastic structural distortions and misalignments, which do not impact image quality but rather LoS pointing bias and knowledge.

Jitter can also impact the performance of other vibration-sensitive electro-optical devices such as cameras and other optical sensors used in vision-based navigation systems. Jitter can also be a significant factor in the performance of optical communications terminals in which stabilized laser beams are used for high data rate communications links, either in space-to-space or space-to-ground applications.

Future NASA missions, both ultra-high precision — e.g., the Habitable Worlds Observatory (HWO) — and more modest pointing missions, will potentially be at risk due to the impacts of jitter. The Habitable Worlds Observatory (HWO), notionally depicted in Figure 1, is a concept for a mission that would search for and characterize habitable planets beyond our solar system. Building upon studies conducted for two earlier mission concepts called the Large Ultraviolet Optical Infrared Surveyor (LUVOIR) and Habitable Exoplanets Observatory (HabEx), HWO would be designed specifically to identify potentially habitable planets around other stars, closely examining their atmospheres to determine if life could possibly exist. Three trades ongoing currently.



**Figure 1: NASA's Habitable Worlds Observatory(HWO):
A Mission with Stringent Jitter Requirements**

THE JITTER PROBLEM

Figure 2 illustrates the basics of the jitter problem: it notionally depicts how an exported vibration disturbance can be exported, from a reaction wheel actuator for example, can be transmitted through a flexible spacecraft structure eventually reaching the sensitive elements of an electro-optical payload.

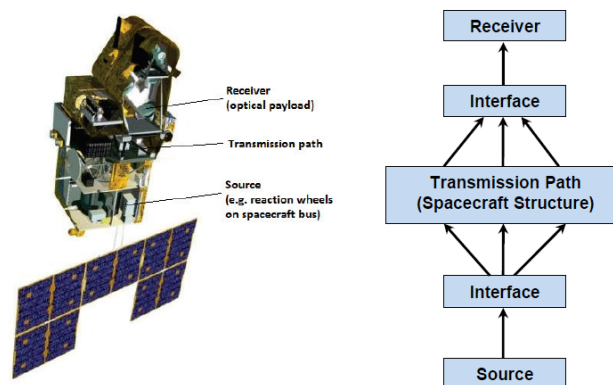


Figure 2: Jitter Causing Disturbance Transmission Through Spacecraft Structure

The deleterious performance impact of micro-vibrations/jitter is clearly depicted in Figure 3 where the time-varying LoS pointing is illustrated in the left portion of the figure [3]. The right portion compares the relative quality of three separate images, which viewed from left to right, portray: the image taken when significant micro-vibration perturbations were present, the image when limited corrective measures had been applied to mitigate the perturbing micro-vibration effects, and lastly when the imager LoS was undisturbed during the image-taking period.

Figure 4 depicts a notional frequency spectrum of spacecraft disturbances, structural flexible

body modes and potential vibration damping approaches [4]. The specified frequency, or frequency range, of an instrument's pointing stability requirement is a fundamental factor that drives a spacecraft's pointing system architecture. As shown in Figure 4, the spacecraft's low-bandwidth Attitude Control System (ACS) operates at relatively low frequencies to point the vehicle to counter external environmental disturbances that occur due to gravity gradient torques, solar radiation pressure torques, and/or torques due to atmospheric drag effects. Low-frequency LoS motion occurs as a result of the ACS control residual, and from uncompensated low-frequency effects such as distortions induced by thermal gradients. High-frequency disturbances come from internally mounted mechanisms and devices (e.g., reaction wheels, solar-array stepper motor drives, antenna gimbal drives, and payload cryocoolers). Continuous reaction wheel vibrations, while the wheels are performing their normal control actuator function, are often the dominant jitter producing disturbance, and accurate representation of the wheel force/torque disturbances is a modelling challenge [5].

Disturbances from reaction wheels, CMGs, and other sources can excite different spacecraft flexible body structural modes, as illustrated in the middle of Figure 4. In general, the spacecraft ACS will not have sufficiently high bandwidth to damp these high frequency vibrations. As indicated in Figure 4, a technique called 'payload assist' can extend the effective ACS bandwidth. In payload assist, a direct measurement of the payload instrument telescope's boresight pointing error is made using payload-measured guide stars. Payload assist increases the bandwidth of the ACS by providing higher-frequency attitude information than the star trackers. Figure 4 illustrates the overlapping frequency ranges of active stabilization (e.g., the use of fast steering mirrors for image motion compensation) and simple passive isolation systems (i.e., simple mechanical low-pass or pass-band filters on which reaction wheels are mounted).

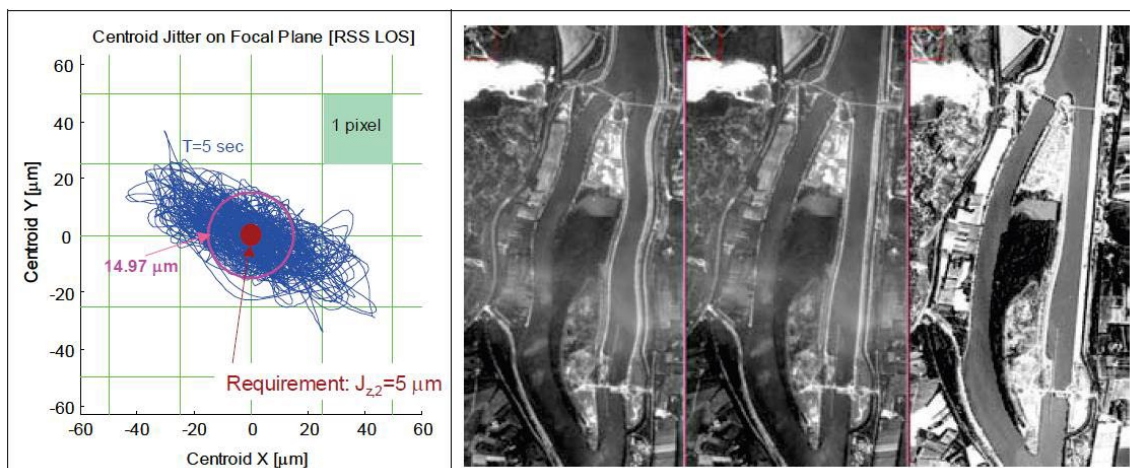


Figure 3: Example LoS Pointing Errors and the Resulting Effects on Image Quality

QUALITATIVE ASSESSMENT OF JITTER

Tighter jitter requirements lead to challenges during design and test. Table 1 depicts a qualitative assessment of the difficulty of meeting successively more demanding jitter requirements [2]. In

general, the more demanding the jitter requirement, the greater is the need for interdisciplinary and system-level solutions, in the vehicle design and test program formulation. In the “blue” category, only basic testing is needed to ensure no unexpected behavior. In the “green” category, component exported force and torque testing (i.e., disturbance source characterization testing) should be planned, and structural transmissibility testing should be considered as part of the modal test plan. In the “yellow” category, testing should be pursued at the component, subassembly, and vehicle levels to verify that the system and its components are characterized, and the jitter requirement is met. The “red” category challenges the state of the practice. Active vibration cancellation or other innovative solutions may be required.

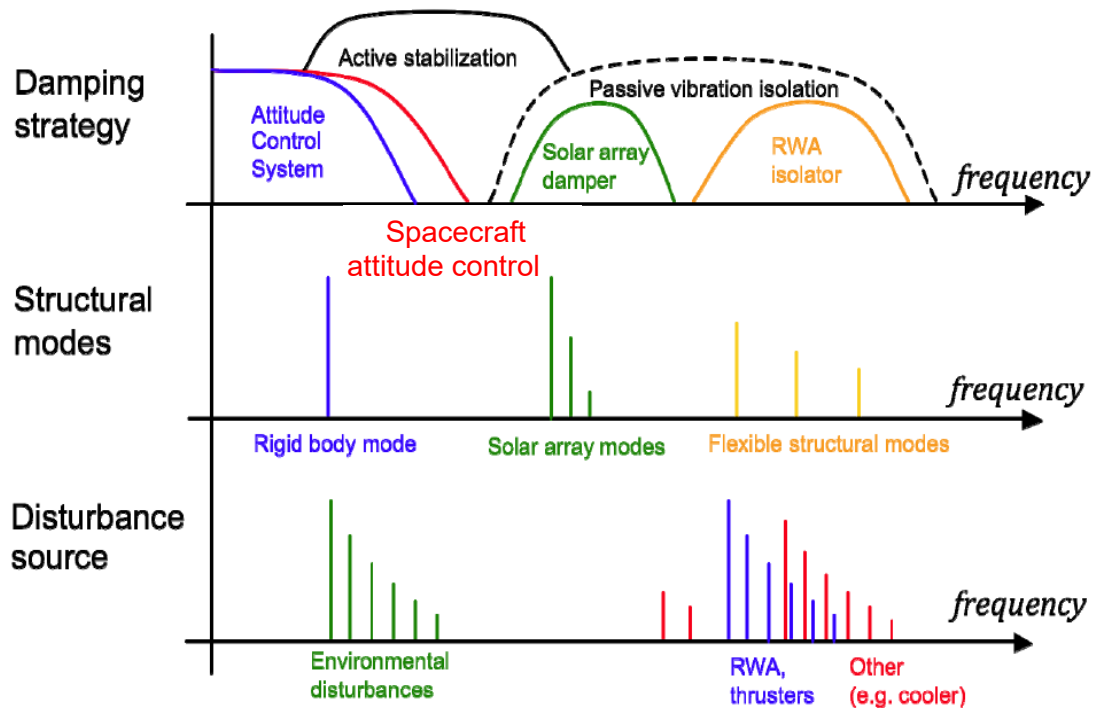


Figure 4: Notional Frequency Spectrum of Spacecraft Disturbances (From Ref 4)

JITTER RULES OF THUMB

Table 2 below summarizes, in a concise and compact format, a quantitative assessment of the difficulty of meeting jitter requirements. Table 2 illustrates which micro-vibration 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. Reference 2 provides a set of ‘rules of thumb’ that correspond to the various cases of performance requirements called out in Table 2. These rules of thumb will be captured and expanded upon in the NASA Jitter Handbook.

Table 1: Qualitative Assessment of Difficulty of Meeting Jitter Requirements

Jitter Requirement	Importance of Considering Jitter “Up-Front”
milliradians	Not considered a challenging requirement
microradians (arcsec*)	Important consideration in spacecraft design & architecture
nanoradians (milli-arcsec)	Design driver; needs to be addressed “top to bottom” in system architecture & design, analysis plans, and test plans
picroadians (µarcsec)	Beyond current state of the practice; entails significant challenges and risks in system architecture & design, analysis, and testing

Table 2: Rules of Thumb for Initiating and Approaching New Micro-Vibration Design

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 → 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 → 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

JITTER HANDBOOK FRAMEWORK

The NASA Jitter Handbook will be organized in as simple and straightforward a manner as possible to allow for easy use by all envisioned users. Per the 2019 NESC-sponsored jitter workshop recommendation the handbook development team at that NASA will capture jitter engineering guidelines, lessons learned, and best (preferred) practices for managing and mitigating spacecraft jitter. The emphasis will be on defining, in sufficient detail, a recommended jitter engineering process and methodology. Guidance for how to best tailor the baseline jitter engineering process/methodology for various classes of spaceflight missions will also be provided. As such the handbook will likely remain agnostic to the use of specific jitter engineering tools.

Table 3 below is a very preliminary framework for the NASA Jitter Handbook. The intent of the handbook is to educate, provide insights, capture best practices, and provide a standard reference for discussion among mission teams. The handbook will be a resource primarily intended for jitter engineering practitioners. However, it can serve multiple audiences: (1) early-to-mid career discipline-level engineers, (2) system engineers, (3) payload/instrument engineers, (4) subsystem lead engineers, (5) project managers, and (6) project scientists.

The handbook will attempt to address the known jitter engineering challenge areas, which are:

- Jitter is a systems problem with limited experience base: Jitter is a multidisciplinary effort (Systems, Optics, L&D, Mechanical Systems, GNC, and more) crossing multiple spacecraft subsystems with limited set of practitioners across NASA.
- Importance of Requirements definition: Observatory level requirements flowed down to lower levels of assembly, budgets/allocations/performance metrics/margins; project WBC/contracts don't necessarily match the physics of the problem.
- Disturbance requirements and modeling: Time or frequency domain. Application point (source) vs. measured at interface. Usually, cannot get transfer function matrix from operational tests.
- Wide Finite Element Model (FEM) frequency range (0.1-500 Hz) and model correlation.
- Requires combination of time and frequency domain analysis results.
- Verification testing challenges: Testing limitations such that typically jitter is a Test-As-You-Fly exception. Expensive and time consuming to perform full-up system-level dynamic interaction testing - only as "flight-like" as feasible in Earth's 1-g environment. System-level verification typically done by analysis. Managing the test and analysis interplay and adapting to the timeline of available information/data.
- Background noise on testing interferes with disturbance source characterization and creates challenges for dynamic interaction test. Often a signal-to-noise problem.

Assuming the kickoff of the handbook development effort in early CY25 it is foreseen that Version 1.0 of the Jitter Handbook will be delivered in April 2026, including the several mission jitter engineering case studies as Appendices. Subsequent updates and additions to Version 1.0 of the handbook will be conducted by the NESC Technical Discipline Teams (TDTs) as necessary.

CONCLUSIONS

Spaceflight mission hosting high-performance vibration-sensitive optical sensor payloads with stringent pointing stability requirements are especially challenged in the areas of predicting, managing, controlling, and testing spacecraft line-of-sight (LoS) jitter. While some textbooks and references in the aerospace literature may touch on the subject of jitter, a formidable multidisciplinary engineering task, the details of specific flight proven methodologies and techniques used by today's jitter engineering practitioners are not readily accessible. Jitter is a niche engineering area with few NASA subject matter experts (SMEs) and no established pipeline for the future.

NASA has no established engineering reference document with guidelines and best practices for managing and mitigating spacecraft jitter. To fill this knowledge gap the NASA Engineering

and Safety Center (NESC) has undertaken the task of developing a NASA Jitter Handbook which would include lessons learned and best practices for design, analysis, and test, along with operational guidelines to mitigate jitter. The expectation is to develop several case studies that will form the core of the handbook.

Technical collaboration on this handbook with NASA-external organization is desired and should be feasible under the right conditions. Currently this NESC activity is focused on a NASA-centric unclassified Handbook but opportunities exist for expanded participation and collaboration with other aerospace engineering organizations.

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