NASA/TM–20210017871

Spacecraft Line-of-Sight Jitter Management and Mitigation Lessons Learned and Engineering Best Practices

Cornelius J. Dennehy
Langley Research Center, Hampton, Virginia

Aron A. Wolf
Jet Propulsion Laboratory, Pasadena, California

Davin K. Swanson
Raytheon Intelligence and Space, El Segundo, California

June 2021

NASA STI Program Report Series

NASA/TM–20210017871

Spacecraft Line-of-Sight Jitter Management and Mitigation Lessons Learned and Engineering Best Practices

Cornelius J. Dennehy
Langley Research Center, Hampton, Virginia

Aron A. Wolf
Jet Propulsion Laboratory, Pasadena, California

Davin K. Swanson
Raytheon Intelligence and Space, El Segundo, California

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

June 2021

Acknowledgments

The authors would like to thank all the jitter workshop participants for their passion and enthusiasm for the subject of spacecraft jitter engineering. The peer reviewers, Steven Gentz (NESC/Marshall Space Flight Center), James O'Donnell (NESC/GSFC), Donald Carter (Raytheon Intelligence and Space), and Oscar Alvarez-Salazar (JPL), who greatly contributed to the technical quality of this paper, are acknowledged by the authors for their meticulous scrutiny. Michael Hagopian, a workshop participant/presenter, is to be credited with the formulation of the five jitter analyses and test best practices listed in Section 3. Lastly, the authors would be remiss if they did not extend their heartfelt thanks to Dee Bullock at the NESC for her attention to detail in preparing this paper for publication. The research described here was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Table of Contents

1.0 Introduction **1**
2.0 Overview of the Workshop **4**
3.0 Key Workshop Conclusions **6**
3.1 General Recommendations 7
3.2 Jitter Terminology Definition Variability 7
3.3 Jitter is a Systems Problem 9
3.4 On-Board Instrumentation and In-Flight Demonstrations 13
3.5 Jitter Engineering Guidelines Handbook 15
3.6 Application of MUFs 16
3.7 Consideration of Streamlined/Tailored Approaches for Non-Flagship Missions 19
4.0 Summary and Go Forward Plans **20**
5.0 References **20**
Appendix 1. Summary List of Jitter Workshop Findings and Recommendations **22**

List of Figures

Figure 1. Example LoS pointing errors and the resulting effects on image quality. 2
Figure 2. Notional frequency spectrum of spacecraft disturbances (bottom), rigid body and flexible body structural modes (middle), and potential vibration damping approaches (top).[4] 3
Figure 3. Group image of NESC Jitter Workshop participants. 5
Figure 4. Illustration of image motion comprising displacement, smear, and jitter.[11] 8
Figure 5. An example set of MUFs as a function of model maturity and frequency.[15] 18

List of Tables

Table 1. NESC Jitter Workshop Presentations 5
Table 2. Qualitative Assessment of Difficulty of Meeting Jitter Requirements 11

Nomenclature

ACS	Attitude Control System
BP	Best Practices
CMG	Control Moment Gyro
CONOPS	Concept of Operations
CoP	Community of Practice
DoD	Department of Defense
ESA	European Space Agency
FEM	Finite Element Model
GN&C	Guidance, Navigation, and Control
GOES	Geosynchronous Observational Environmental System
GSFC	Goddard Space Flight Center
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LEO	Low Earth Orbit
LoS	Line of Sight
MUF	Model Uncertainty Factor
NASA	Nation Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
SME	Subject Matter Expert
T	Exposure Interval of Length
TPS	Thermal Protection System

Abstract

Predicting, managing, controlling, and testing spacecraft line-of-sight (LoS) jitter caused by micro-vibrations due to on-board internal disturbance sources is a formidable multidisciplinary engineering task. It is especially challenging for those missions hosting high-performance (e.g., nano-radian/milli-arcsecond class), vibration-sensitive optical sensor payloads with stringent pointing stability requirements. The Nation Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are planning technically aggressive spaceflight missions that include ultra-high-performance optical payloads with delicate, highly vibration-sensitive scientific and observational instruments. The guidance, navigation, and control community of practice will need to leverage collective experiences and document their best practices and lessons learned to address future micro-vibration challenges. To identify lessons learned and best practices the NASA Engineering & Safety Center sponsored a 2-day Spacecraft LoS Jitter Workshop in late 2019. The workshop's goal was to provide a multidisciplinary forum to elicit deeper understanding of the issues related to addressing the spacecraft LoS jitter/micro-vibration problem. The primary objective was to identify, document, and share lessons learned, best practices, and preferred options for jitter-related analysis and test activities. Representatives from NASA, ESA, along with NASA's industrial partners, independent consultant subject matter experts, and members of academia participated in the workshop. This paper describes the motivation for the workshop and summarize the identified findings and recommendations.

1.0 Introduction

In the process of formulating their next generation of Space and Earth flagship-class science missions, the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) intend to push technology and engineering towards higher performing payloads and instruments. This trend towards more capable systems will undoubtedly drive guidance, navigation and control (GN&C) engineers to accommodate and operate payload instruments with increased detector resolution and sensitivity, and longer observational dwell times, leading to more stringent nano-radian/milli-arcsecond class requirements for pointing stability or jitter.

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 driving requirement for high-quality imaging .[1] In this paper, the term "jitter" refers to uncommanded 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. Predicting, managing, controlling, and testing spacecraft LoS jitter caused by micro-vibrations from on-board internal disturbance sources often presents a formidable multidisciplinary engineering challenge. This is especially true for those missions hosting high-performance optical sensor payloads with stringent pointing stability requirements.[2]

The performance impact of micro-vibrations/jitter is clearly depicted in Figure 1[3] where the time-varying LoS pointing is illustrated in the left portion of the figure. 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.

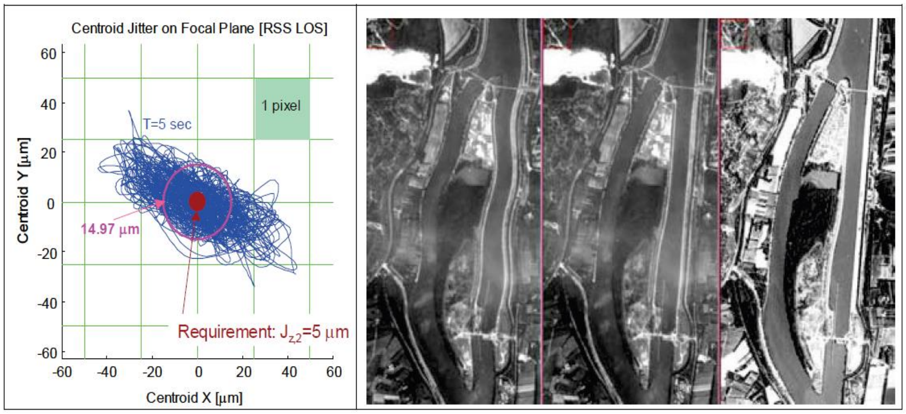

Figure 1. Example LoS pointing errors and the resulting effects on image quality (from Reference 3).

Figure 2 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 2, 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] Control moment gyros (CMGs) are an alternative to reaction wheels that are popular on remote sensing missions and are preferred over reaction wheels from a jitter perspective. However, disturbances from reaction wheels, CMGs, and other sources can excite different spacecraft flexible body structural modes, as illustrated in the middle of Figure 2. In general, the spacecraft ACS will not have sufficiently high bandwidth to damp these high-frequency vibrations. As indicated in Figure 2, 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.[4] Payload assist increases the bandwidth of the ACS by providing higher-frequency attitude information than the star trackers. Figure 2 illustrates the over-lapping 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).

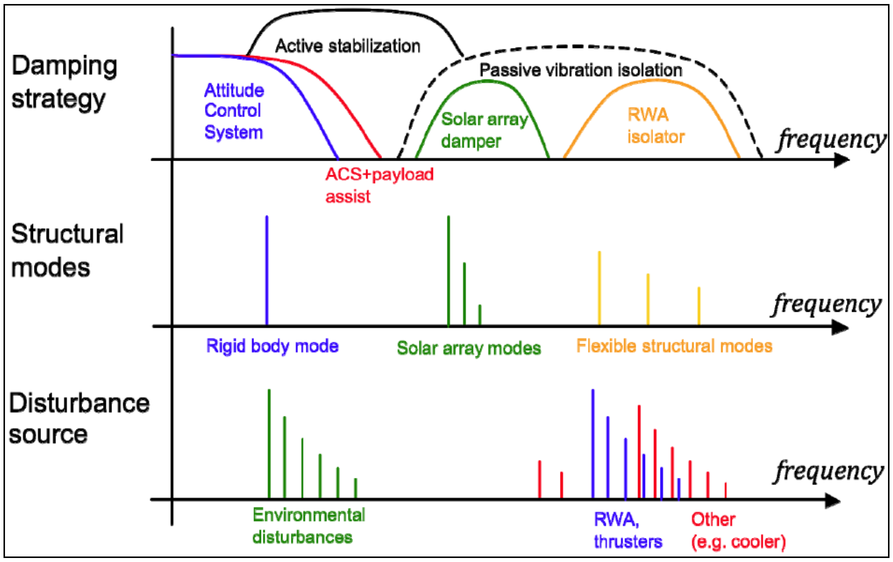

Figure 2. Notional frequency spectrum of spacecraft disturbances (bottom), rigid body and flexible body structural modes (middle), and potential vibration damping approaches (top).[4]

There is no universal solution to spacecraft jitter problem since each platform has its own unique set of payload instruments, disturbances, flexible modes, mass/power constraints, mission assurance requirements, and cost constraints. Moreover, experience has shown that a spacecraft's dynamic response can be sensitive to structural details resulting in "chaotic" behavior that is challenging to model. Thus, even nominally "identical" physical spacecraft structures can have different high-frequency behaviors that impact jitter. To achieve the best possible pointing stability at all frequency ranges, guidance, navigation, and control (GN&C) engineers will need to employ all existing vibration control techniques, including attitude control, attitude control with payload assist, highly stable optical benches for co-locating ACS and payload sensors, active stabilization, and passive vibration isolation.

To identify lessons learned and best engineering practices, the NASA Engineering & Safety Center (NESC) sponsored a 2-day Spacecraft LoS Jitter Workshop in late 2019. The workshop's goal was to provide a multidisciplinary forum to elicit deeper understanding of the issues related to solving spacecraft LoS jitter/micro-vibration problems. Please note that for the remainder of this paper the NESC Spacecraft LoS Jitter Workshop will be referred to simply as the 'workshop.'

NASA, ESA, and other international space Agencies, with their industry partners, have a long, technically rich, and impressive history of solving the difficult engineering problems associated with managing, controlling, and testing spacecraft jitter and micro-vibrations. For insights into the relevant historical experiences, Reference 2 provides a survey-level view of multiple spacecraft micro-vibration/jitter problems, experiences and solutions. The GN&C Community of Practice (CoP) may leverage and build upon the collective set of experiences and lessons learned in this specific technical area to better address jitter/micro-vibration challenges expected in future missions. This paper complements and builds on Reference 2 by documenting specific jitter best practices that emerged from the workshop.

In addition to addressing the jitter management needs of future high-performance, flagship-class missions, the workshop considered approaches for lower cost 'commercial-class' missions with less stringent, yet mission-critical, jitter requirements. Section 3.7 will address in detail the need for a paradigm shift in order to create a lower-cost jitter mitigation process for ‘commercial-class’ missions that use relatively high-volume production practices.

While this paper will primarily focus on the outcomes of the workshop it will not be limited to this event. The authors will include comments, observations, and developments that have occurred since the workshop occurred.

Section 3 of this paper summarizes the identified findings and recommendations that emerged from the workshop. A potential go-forward plan for moving out on a path to pursue and fulfil these recommendations to address spacecraft LoS jitter/micro-vibration engineering challenges are discussed at the conclusion of this paper. The authors envision holding a second, possibly inter-Agency jitter workshop, hosted by NASA or ESA in the near future, perhaps as early as late 2021.

2.0 Overview of the Workshop

The workshop’s goal was to provide an informal, interactive multidisciplinary forum for subject matter experts (SMEs) from the GN&C, Mechanical Systems, Structural Dynamics, and other relevant engineering disciplines within NASA and ESA to share their knowledge and to elicit deeper understanding of the issues related to solving the spacecraft LoS jitter/micro-vibration problem. Collective NASA-ESA experiences have reinforced the imperative of having a multidisciplinary perspective on this problem.

A primary objective was to identify, document, and share lessons learned, best practices, and preferred options for jitter-related activities in the following technical areas: spacecraft pointing system architecture trades and definition, requirements definition and flowdown, modelling and simulation tools and techniques, subsystem and component characterization testing, spacecraft system-level end-to-end testing, and overall jitter/micro-vibration risk-reduction approaches and techniques. The workshop was successful in identifying technical and programmatic contractual issues, barriers, and challenges related to solving the spacecraft LoS jitter/micro-vibration problem.

Participants in the workshop included representatives from NASA (including the Jet Propulsion Laboratory (JPL)) and ESA, along with industrial partners, independent consultant SMEs, and members of academia. The workshop attendees (see Figure 3) included specialists in GN&C, pointing systems, mechanisms, structures, finite element modelling, isolation systems, system engineering, and system testing. Selected participants made presentations on a variety of relevant topics, listed in Table 1.

One other motivation for the workshop was to address a common interest in developing an efficient process for consistently creating implementable, reliable, and well-performing solutions to the spacecraft LoS jitter problem. The workshop was an opportunity to share NASA and ESA viewpoints on jitter with the broader community and a chance to hear industry viewpoints on jitter.

Figure 3. Group image of NESC Jitter Workshop participants.

Table 1. NESC Jitter Workshop Presentations

Presentation Topic	Presenter	Organizational Affiliation
Jitter Workshop Introductory Remarks	Neil Dennehy	NESC (GSFC)
Jitter experiences: predicting, managing, controlling, and testing spacecraft jitter	Mike Hagopian	Adnet, Inc.
Jitter Process 101	Gary Henderson	The Aerospace Corporation
Pointing error metrics	Mark Pittelkau	Independent consultant
Active Solutions to the Spacecraft Jitter Problem	Fabrice Boquet	European Space Agency (ESA)
EllipTool	Carl Blaurock	Elliptical Engineering
Microvibration activities at Surrey	Guglielmo Aglietti, Alessandro Stabile	Surrey / UK
Influence of microvibration requirements on mechanism design	Geert Smet	European Space Agency (ESA)
Roman Space Telescope integrated modeling and jitter	Alice Liu	NASA GSFC
Potential Development of Low Disturbance Ball Bearings	Bill Bialke	Independent consultant

Some examples of key questions explored at the workshop are:

- What does industry need from NASA or ESA, and/or from the GN&C academic research community to help architect, design and develop space platforms with stringent LoS jitter requirements?
- What modelling/analysis methods and tools are required to synthesize jitter solutions?
- What ground-test and/or in-flight demonstrations are needed to support the necessary verification processes and the needed technology development advances?

3.0 Key Workshop Conclusions

The individual workshop presentations stimulated productive technical interactions amongst the SME participants. Findings and recommendations focusing on various specific aspects of jitter management and mitigation are discussed in this section and are summarized in the following list of best practices (BPs).

BP #1 Fully appreciate and understand the jitter performance challenge

- Make informed architectural choices (e.g., common optical benches for instruments and/or ACS sensors, isolation systems, control system bandwidths, etc.) for the given pointing and pointing stability requirements. This should be done in collaboration with the mission stakeholders.

BP #2 Fully understand all the potential disturbance sources

- Early tests, particularly for key components/subsystems (e.g., reaction wheel disturbance characterization tests at the vendor) that affect jitter, are critical as they allow for refinements to systems early in the design process. Consideration of all potential versus expected sources of disturbance is encouraged.

BP #3 Pursue an incremental jitter analysis/test program that mitigates risk over time

- A successful spacecraft LoS jitter management and mitigation solution requires an understanding of the behavior of key components through test, and of the overall system through a combination of test/analysis consistent with complexity and uncertainty. There are multiple ways to verify system pointing stability/jitter performance, but for complex systems with challenging requirements a comprehensive incremental test program is required to anchor even the best analysis, and, at a minimum, a systems dynamic interaction test is required.

BP #4 Build in flexibilities to overcome unexpected in-flight pointing stability performance issues

- Ground test limitations (e.g., boundary conditions, gravity effects, test durations, etc.) push systems with stringent jitter requirements towards additional jitter mitigation approaches, which can be redundant or potentially overly conservative (e.g., multiple layers of mechanical noise isolation systems) to cover uncertainties. Alternatively, operational flexibilities can be used to mitigate dynamic interactions within the spacecraft, which can be difficult to fully characterize prior to launch. Gaining insight into key system operational flexibilities and constraints requires diagnostic capabilities within the instruments or through additional instrumentation to improve pointing stability performance in-flight either by on-board adjustments and/or allowing model correlation on the ground.

BP #5 Include payload and spacecraft bus jitter measuring instrumentation to assess modelling and test results with in-flight pointing stability performance, and to maximize ability to mitigate jitter with in-flight adjustments

- Deploying in-flight the same precision instrumentation used during ground test is critical for multi-mission programs, and for missions with stringent jitter requirements, as it enables trending, operational updates, anomaly resolution, and informing future designs.

Given the positive feedback received on the workshop, the authors see benefit in holding a second, possibly inter-Agency Jitter Workshop, hosted by NASA or ESA in the near future, perhaps as early as late 2021, subject to the constraints on face-to-face meeting due to the on-going COVID-19 pandemic.

3.1 General Recommendations

Three general high-level recommendations resulted from the workshop:

R-1 NASA and ESA should coordinate on planning and executing a second face-to-face inter-Agency Spacecraft LoS Jitter Workshop as soon as practical.

R-2 NASA to consider forming Jitter Workshop Working Groups to perform specific jitter related tasks (e.g., the development of Jitter Engineering Guidelines Handbook), which would seek inputs from across organizations and provide progress updates at future Spacecraft LoS Jitter Workshops.

R-3 A flight project's jitter engineering team should establish a strong working relationship with stakeholders (e.g., scientists planning Earth and Space science missions) where LoS jitter considerations are paramount.

With a few exceptions, the majority of the recommendations documented in this paper are directed to the NASA GN&C CoP for post-workshop follow-up action. It is envisioned that the recommendations documented in this paper will all be discussed, dispositioned, and ultimately assigned to individual Jitter Workshop Working Groups at the next spacecraft LoS jitter workshop.

3.2 Jitter Terminology Definition Variability

The workshop participants were in consensus that no single commonly understood and used definition of "jitter" in the context of LoS pointing and pointing stability exists. Reference 6 offers a set of useful working definitions, provided in non-technical language. As Dr. Henderson wryly observes in this work the answer to the question "What is Jitter?" will depend on who exactly is being asked that question. This reflects the need to converge on a single set of definitions accepted and understood by the multidisciplinary community to facilitate sharing and reuse of analysis methods, design concepts, and system engineering processes. The definitions of jitter and related terms have advanced over recent decades with multiple authors making fundamental advancements in the definition of jitter.[7-10] More recently, jitter engineers have gravitated towards the use of Optical Transfer Functions in the discussion of jitter definition and related terms.[11]

Fundamentally, jitter is made of full cycles of image motion across the detector. Jitter is usually considered medium to high frequency in nature, and often periodic. It is sometimes defined as any pointing error that is beyond the control bandwidth of the ACS. In addition to being frequency-dependent, jitter is usually specified over a time period associated with a sensor's integration time requirement. The term "smear" refers to partial cycles of motion (i.e., low frequencies) over the characteristic time period. This produces motion across the detector, analogous to what happens when someone bumps you while taking a photograph. "Pointing error" represents an offset in the image location on the detector from its intended or commanded location.

Reference 11 provides another set of definitions for jitter and associated terms. Figure 4 depicts image motion comprising displacement, smear, and jitter.[11] Displacement is the average image offset over the exposure interval of length (T). Smear is due to a linear motion over the interval and is equal to T times the smear rate, where the smear rate is the average slope of the image motion over the exposure interval. Jitter is the residual motion after displacement and smear are removed from the image motion. Smear results in a streaked image and jitter causes an image to be blurred.[11]

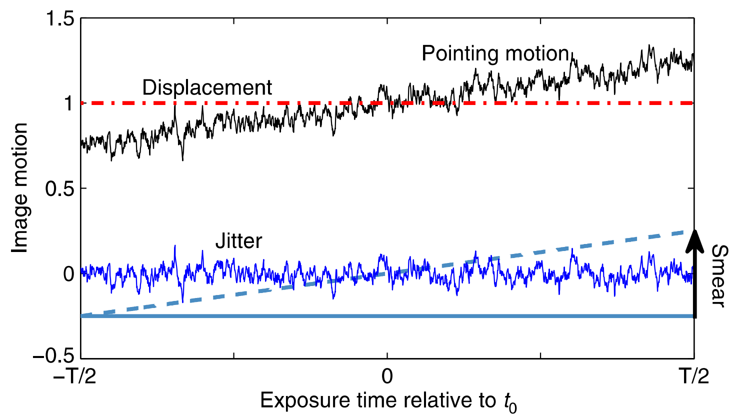

Figure 4. Illustration of image motion comprising displacement, smear, and jitter.[11]

There are other image motion and pointing errors that are not captured by jitter that impact mission performance. Examples are, static pointing error due to observatory alignment errors, quasi-static pointing error due to drift induced by the thermal environment and pointing error due to thermal snap excitation of boom or solar array flexible modes excitation. ACS feedback sensor nonlinearities can cause low-frequency pointing errors and higher-frequency errors near the ACS control bandwidth.

Repeatability of an observation comes into play here as well. One can specify repeatability through tighter requirements on allowable motion/jitter/smear but that does not take advantage of common-mode pointing errors resulting in unnecessarily tighter pointing requirements. But, using common-mode pointing errors implies being able to predict with accuracy through modelling.

The details of the mathematical definitions of each of these types of motion or error matter in specifying and verifying pointing/pointing stability budgets and other system requirements. The act of reconciling the various definitions across mission partners and stakeholders, or across the multiple participants on a single flight project team, could be simplified or eliminated with a common set of definitions.

<u>Findings:</u>

F-1 There are multiple, similar but not identical, definitions of jitter and associated terms in use across the jitter engineering community.

Recommendations:

R-4 Standardize an approach (e.g., Reference 11) as the basis for engineers and scientists to communicate concerning instrument jitter requirements and performance metrics.

R-5 Converge on common jitter terminology, which can be documented in the Jitter Engineering Guidelines Handbook.

3.3 Jitter is a Systems Problem

Understanding and managing spacecraft jitter is a multidisciplinary task, involving expertise in structural dynamics (e.g., stiffness, isolation, damping), control systems (e.g., bandwidth, actuators, sensors), mechanisms (e.g., reaction wheels, coolers, deployables, and other disturbance sources), and system engineering (e.g., trade studies, requirements flowdown and allocation to subsystems). Successful jitter management requires collaboration and involvement of systems engineers, particularly in definition and flowdown of requirements and Concept of Operations (CONOPS), with experts across multiple engineering disciplines. This critically important work must start early in the mission formulation phase and will of course continue throughout the design and development phases of a flight project lifecycle. The lead system engineer must understand the top-level mission requirements to flowdown specific requirements to the subsystem/component level. Solutions to jitter often require trades across discipline or subsystem lines. For example, reducing a reaction wheel’s exported force/torque disturbances may not be a feasible path for a flight project to pursue due to cost and schedule constraints so isolation or structural design modifications may be required.

Disturbance sources may be located on the spacecraft bus or in the instrument(s). Disturbances may be attenuated or amplified by the structural load path to the instrument node(s) of interest. Some disturbances result directly in open-loop jitter (bulk instrument or scanner motion), while others couple with other components of the system indirectly (e.g., reaction wheel control error at the ACS bandwidth, which effectively becomes a platform disturbance at a frequency different than the reaction wheel). Some interactions lead to instrument performance issues or degradations within the instrument that degrade the image without necessarily affecting LoS jitter.

The spacecraft bus is controlled by the ACS, while instrument LoS may be controlled by an additional scan mechanism servo or other mechanism. There can be complex interactions between bus and instrument control systems (e.g., scanner operation affecting ACS and exciting spacecraft flexible structural modes). Control system errors due to sensor/actuator nonlinearities or other causes, can lead to varying LoS error over field-of-view, orbit, or lifetime. ACS sensor and instrument reference frames are often non-collocated, and thermal gradients can move relative LoS differently across multiple spacecraft instruments.

Systems engineering efforts begin with defining the appropriate architecture to achieve the required pointing performance. This requires an interdisciplinary jitter team. The workshop highlighted the disconnect between system architects/image analysts/scientists and LoS/Jitter SMEs. This disconnect can be resolved by including representatives from these disciplines/subteams as part of the project jitter team. Early requirements definition and flowdown guided by modelling and simulation (rather than exclusively by heritage rules of thumb that can be overly conservative) is important, including early definition of pointing stability error budgets. There will be a strong drive by parts of the team to focus on the development of an integrated model to simulate and predict jitter performance, which is to be expected, but careful attention is needed to ensure the modelling and simulation activity does not inhibit, or worse paralyze, progress on the system design activity. Flight project experiences have revealed how hard it is to balance those two activities especially in the early phases of the life cycle.

Appropriate features should be designed into the system to enable adjustments over the entire design and development cycle, and during in-flight operations. The architecture should contain flexibility to allow designers to adapt to changing models and test data. Key disturbance sources must be identified, modelled, and mitigation methods developed if necessary. All vibration-sensitive elements including items outside the primary instrument(s) (e.g., clock chips, star trackers) must be identified. This may include balancing reaction wheels, reducing structural interactions (e.g., through isolation), passive vibration isolation, and/or active jitter control. Discussions of jitter management and mitigations should include the payload designers (who are typically the science team on NASA missions) as well as the ground system developers who are responsible for the post-collection ground software processing of instrument data streams to remove jitter artefacts.

Obviously, throughout this design evolution process, systems engineers should carefully consider and trade the balance between the applications of multiple jitter mitigation methods and the added system complexity of applying them. System engineering must be aware of potential conflicts of interest, with respect to margins and risks, within the jitter design team. Systems engineering should not allow one design team member to hold excessive conservatism for their hardware in an attempt to limit their own individual risk. Instead, systems engineering should be enforcing a more integrated project-optimized approach to risk management. To ensure the entire end-to-end system is optimized, excessive conservatism should be avoided in the design and requirements definition process. Pointing stability performance margins should be assessed at the system level to avoid too many layers of margin (and hidden margin) across component/subsystem providers.

Performance and sensitivities must be understood through a balanced program of modelling, analysis, and testing. Models should be anchored in the test program and by data from in-flight performance/operation of identical systems. Testing may be needed at the component level (e.g., wheels and other key disturbance sources) and system/subsystem levels (e.g., speed sweeps of wheels mounted to an instrumented bus with test instrumentation and science instruments operating, or testing examining instrument errors in response to a direct optical stimulus or servo error with the spacecraft suspended). The complexity of the test program is dependent on the required level of pointing stability performance.

The early consideration of jitter mitigations by system engineering is critical to successful program execution. A common negative experience among workshop participants was that projects without adequate resources to identify all sources of jitter issues and ways of mitigating them from design inception will eventually identify jitter-related problems late in system development when fixes are more expensive and cause greater schedule impact.

Methods for managing jitter throughout the design process must be included from the beginning of the payload and spacecraft bus design process. Designs should provide for ease of tunability so that changes can be implemented in response to updated analysis or test data without major changes to interfaces (e.g., isolation or stiffness control at critical interfaces or tuning masses at critical response areas). Management of the mission's CONOPS is critical (e.g., avoiding or minimizing jitter-producing events during science observations, or managing reaction wheel momentum to keep the wheels away from speeds that excite problematic modes). Disturbance levels can sometimes be reduced at the source (e.g., better balancing of reaction wheels). Tunability can be added to some sources (e.g., cryocoolers) ensuring that problem modes can be avoided by changing the forcing function frequency content. Flight experiences have shown the value of having tunable disturbance sources to provide the ability to tune (move) away from a structural resonance peak response.

Tighter jitter requirements lead to challenges during design and test. A qualitative assessment of the difficulty of meeting successively more demanding jitter requirements is shown in Table 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.

Table 2. Qualitative Assessment of Difficulty of Meeting Jitter Requirements

Jitter Requirement	Importance of Considering Jitter "Up-Front"
Milli-radian	Not considered a challenging requirement
Micro-radian (arcsec*)	Important consideration in spacecraft design & architecture
Nano-radian (milli-arcsec)	Design driver; needs to be addressed "top to bottom" in system architecture & design, analysis plans, and test plans
Pico-radian (μarcsec) *1 arcsec ≈ 5 μradian	Beyond current state of the practice; entails significant challenges and risks in system architecture & design, analysis, and testing

The common systems engineering practice of specifying subsystem requirements at interfaces can conflict with accurate dynamic analysis. Dynamics does not always break cleanly at prescribed system interfaces. System-level performance is a result of coupled dynamics between all components of an observatory (i.e., payload instruments, spacecraft bus, solar arrays, etc.) and attempting to cleanly cut/break interfaces is prone to the introduction of unwanted conservatism. An integrated spacecraft model and jitter simulation should be built as early as possible to understand system and subsystem dynamics and sensitivities, refine error budget allocations, to 'tune' the design as it matures, and to guide the jitter test program. Model uncertainty factors (MUFs) should be used as appropriate to protect against unanticipated jitter increases (see Section 3.6). The integrated model can be architected so that it is built and enhanced in stages. An early, integrated system finite element model (FEM) at the appropriate level of fidelity, with initial definition of input forcing functions, can be used for open-loop structural performance computations. Initial assessments generally use this model with discrete pre-defined forces in a linear frequency domain analysis. An ACS model should be added to represent transient forces resulting from ACS functions (other than stationary random inputs and steady state harmonics) suitable for use in a time-domain analysis. The ACS model should grow to incorporate detailed models of all attitude knowledge sensors and torque/force actuators.

Lastly, workshop participants agreed that many gross errors are caused by confusion or misunderstandings of engineering units (e.g., confusion between milli-radian and arc-second angular measurement units) or lack of rigorous discipline regarding the definition and use of coordinate systems. An established GN&C engineering preferred practice is to define and document the coordinate frames and the system of units (and associated conversion factors) and rigorously enforce compliance. Furthermore, systems engineering should ensure understanding and compliance to these units and coordinate systems throughout the project.

Findings:

F-2 Managing jitter is a highly multidisciplinary systems-oriented task, requiring involvement of an experienced multidisciplinary team, particularly for more demanding spacecraft jitter requirements (e.g., at the nano-radian or pico-radian level).

F-3 Jitter management/mitigation should be addressed in the early project phases when many impactful system architectural decisions are most often made.

F-4 Sources of uncertainty should be well understood and driven down as the design matures.

F-5 Most gross errors are caused by confusion or misunderstandings of units (e.g., confusion between nano-radians and milli-arcsecond units of angular measure) or lack of discipline regarding coordinate systems.

Recommendations:

R-6 Create and maintain an experienced, multidisciplinary team to manage jitter throughout the project lifecycle.

R-7 Carefully consider jitter management and mitigation during the mission formulation phase, including the planning for early test campaigns and developing the capability for performing integrated modelling, simulation, and analyses focused on the areas of greatest jitter uncertainty.

R-8 To optimize the whole system, excessive conservatism should be avoided in the design and requirements definition process, and margins should be assessed at the system level to avoid too many layers of margin across component providers.

R-9 Requirements should be specified in terms of system end-to-end versus interface performance.

R-10 Systems engineering must be aware of potential conflicts of interest, e.g., when one participant is holding excessive conservatism for their hardware to control their own risk vs. a more integrated program approach.

R-11 In the modelling, simulation, and analysis pay careful attention to units and coordinate systems.

R-12 Include science team and ground system team members responsible for the post-processing of instrument data (to remove jitter artefacts) in discussions of jitter management and mitigations.

3.4 On-Board Instrumentation and In-Flight Demonstrations

One of the more engaging discussion topics at the workshop was the apparent need that GN&C engineers have for in-flight jitter-related data. It was repeatedly mentioned that being able to obtain and analyze in-flight system performance data would aid to validate pre-launch models and improve models for follow-on spacecraft. "*Engineers need data too!*", a notable point attributed to NASA Goddard Space Flight Center (GSFC) jitter engineering pioneer John Sudey in the 1980s, was a theme that emerged during the workshop.

In-flight data would allow improved characterization of spacecraft bus and payload disturbances and of the platform's flexible body dynamics. In the latter case, the structural vibration frequencies would be apparent in the in-flight data and could be compared to the pre-launch predications reported by the system FEM. Extraction of structural damping information from the in-flight data is also possible.

In-flight data of a more diagnostic nature could be used to support long-term routine system operations. Gaining proper insight into key component/subsystem operational flexibilities (e.g., SADA step modes, cryocooler drive frequency, component redundancy, adjustable correction profiles, etc.) and constraints (e.g., wheel speed stay-out zones, simultaneous payload instrument operations, etc.) requires in-flight diagnostic instrumentation. This can be used for either directly implementing limited on-board operational adjustments or for the purposes of a comprehensive model correlation on the ground. In particular, deploying the same precision diagnostic instrumentation used during system ground test is critical for multi-mission programs, and for missions with stringent jitter requirements, as it allows trending, refining of system operations, and debugging jitter problems to improve pointing stability/jitter performance in flight.

In general, a system with a payload instrument acting effectively as a jitter sensing sensor is most likely the best in-flight diagnostic instrumentation. Of course, observability would be enhanced with higher bandwidth instrumentation that allows engineers insight into the spectral content of the disturbances that results in the observed LoS performance. For example, the operators of systems with CMGs will often times 'tune' the CMG speed in-flight based upon observations from the primary payload instrument. The same can be said for cryocoolers and other tunable disturbance sources. Thus, typically, engineers are not completely without system performance insights given a lack of specialized inflight jitter diagnostic instrumentation. Without that type of in-flight jitter instrumentation however, engineers will never have the deeper insights needed for purposes of model correlation on the ground. Additionally, that type of *in situ* feedback would also allow for more efficient and streamlined tuning by ground operators.

At the workshop, it was identified that the latest generation of Geosynchronous Observational Environmental System (GOES) spacecraft serves as a positive example of using on-board instrumentation to sense and capture in-flight data to enhance the ability to compensate imagery for deleterious jitter effects.[12,13] Additional on-board instrumentation was added to the first in the latest family of GOES spacecraft to better characterize the system and to enable incremental improvement of later spacecraft in the series. This additional instrumentation resulted in an unintended outcome during early operations when inflight performance showed that jitter reduction was necessary. The instrumentation informed development of mitigation techniques that leveraged in-flight data and additional ground tests. The major conclusion from these workshop discussions was that in-flight jitter related *in situ* measurements combined with in-flight operational flexibility (i.e., sufficient options to adjust system performance) are useful. These should be focused around specific areas of higher uncertainty not readily tested on the ground, including: transient thermal effects, vibration modes of flexible appendages (especially any lightly damped, highly resonant flexible modes), micro-radian level interactions, and stray light entering critical attitude knowledge sensors.

Availability of in-flight data can help compensate for the inability of ground testing to fully replicate the actual operational environment due to gravity effects, orientation, and the need to establish flight-like test boundary conditions. Test opportunities and durations are often limited due to expense or facility availability. The expense and durations required for full-up system dynamic interaction jitter testing has driven the trend for programs to rely solely on system models. While the need to perform sufficient testing, at the component, subsystem, and end-to-end system levels, is seen as critical by the jitter engineers to anchor and verify their models before flight, that perspective is being alarmingly challenged on the basis of test affordability and a perhaps dubious assumption that the system models are technically sufficient to generate accurate pre-launch predictions of the system's jitter performance. This can lead to the use of high "analysis only" MUFs, resulting in overly conservative models and potentially driving more complexity and mass into the system design. Having on-board jitter measuring sensors/instrumentation could provide an in-flight CONOPS modification option(s) through efficient and observable disturbance tuning or operational constraints if the non-test verified models prove to be insufficient.

Design of a common in-flight jitter instrumentation architecture would provide missions the benefits described while minimizing non-recurrent engineering costs. Careful thought would be needed to architect, design, and develop flexible/reconfigurable instrumentation options with the sensitivities and data capture rates for an array of mission types to best support jitter modelling and analysis.

Another fundamental aspect to be considered here in architecting a jitter instrumentation package is the associated telemetry downlink capability. In-flight jitter instrumentation will only be useful if sufficiently high-data rate information can be collected and sent to the ground in a timely manner. One can foresee that for jitter characterization purposes this will translate to relatively large volumes of high-resolution data to be collected on-board and then downlinked to the ground. Data compression techniques may be applicable here to help manage the size of the jitter data packet to be telemetered to the ground. NASA's flagship-class science missions are often architected to be able to store and downlink large volumes of science data, but the ability to do this with a large volume of engineering data is not always present.

Of course, such instrumentation should also be designed to provide sufficient information to system operators to adjust system jitter performance. Obviously, this instrumentation would need to have acceptable size, weight, and power attributes and to have non-intrusive characteristics to be accommodated with minimum impact as part of the system payload or on the spacecraft bus, or ideally in both locations. Conceivably, the jitter measurement instrumentation could take the form of a single miniaturized and highly integrated sensor package (unit), or a distributed sensor-net distributed across the spacecraft bus and the payload instruments. It is understood there would be pros and cons associated with instantiation of a jitter measurement device. For example, a single integrated sensor package unit may not be suitable for obtaining data in the spacecraft's flexible body vibration modes. A flight demonstration could be sought out to raise the Technology Readiness Level of such a package—perhaps as an add on to an existing technology demonstration mission. As regards NASA this might mean a technical collaboration with the U.S. Department of Defense (DoD) or potentially another space Agency (e.g., ESA).

Thinking strategically, it can be seen how including on-board sensors/instrumentation would allow measurements of key performance metrics, which can be exploited to improve performance on future missions. There is limited experience at NASA where on-board sensors have been added to obtain specific data to support modelling and design processes. One relevant example was the Mars Entry, Descent, and Landing Instrumentation activity where on-board sensors were embedded in the Mars spacecraft heatshield to obtain *in situ* engineering data on Thermal Protection System (TPS) performance to support model validation for future TPS applications. Likewise, there will be Developmental Flight Instrumentation included on the Space Launch System launch vehicle and the Multi-Purpose Crew Vehicle spacecraft. The GN&C engineering community can leverage these NASA examples to help make the case for including jitter measurement sensors/instrumentation on future spacecraft having stringent pointing stability requirements.

Perhaps the most powerful strategic argument to be put forward is that by outfitting the payload instruments or the spacecraft bus with some minimally intrusive motion and/or force-measuring sensors, engineers can better anchor their micro-vibration/jitter models for future mission. This would have to be a collaboration with flight project leadership who must manage risk and resources, and with the scientists who 'own' the payload instruments. Both parties would have to see the strategic value of accommodating what they might at first narrowly view as non-essential instrumentation. The expression "a community grows great when a people plant shade trees knowing they will never sit under them" comes to mind in this context. There may be no immediate payoff to the project or mission that agrees to accommodate some form of jitter measurement instrumentation, that payoff might only manifest in a future mission.

Finding:

F-6 There is an imperative need for GN&C engineers to obtain and analyze in-flight jitter related data to allow for in-flight system jitter performance improvements and to validate pre-launch models to support future missions.

Recommendation:

R-13 NASA, in partnership with its industry partners and other space Agencies, should initiate an investigative trade study into miniaturized jitter measurement instrumentation alternatives.

3.5 Jitter Engineering Guidelines Handbook

One overarching conclusion from the workshop is that there is no generally accepted engineering reference on managing and mitigating jitter. Much of the collected wisdom regarding jitter management resides with a small number of SMEs at NASA, ESA, and industry experts. There is a need to make the collected knowledge of these experts available to the next generation of engineers that will be faced with solving jitter problems on future space platforms. While some textbooks and references[2] may touch on the subject of jitter, important details of specific flight-proven methodologies and techniques used by today's jitter SMEs are not readily accessible. Much of this knowledge is treated as proprietary information across industry and is often closely held by the various spacecraft engineering organizations. However, the belief of the workshop participants was that there is much basic jitter engineering 'tribal' knowledge that can be captured in a handbook without compromising any organization's proprietary information.

The GN&C CoP should document the preferred analysis and test methodologies/techniques that have emerged in jitter management over the past decades. Consequently, a recommendation emerging from the workshop is for NASA and/or ESA to create a Jitter Engineering Guidelines Handbook capturing the most relevant lessons learned and best practices. As envisioned by the workshop participants, the handbook would provide a comprehensive set of multidisciplinary design, analysis, test, and operation guidelines that would be extremely helpful to initiate individuals that are unfamiliar with the jitter problem (e.g., early-career engineers or science team members, or project managers). The workshop participants envisioned 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, this handbook would document key jitter-related nomenclature/terminology, including formal mathematical definitions, to establish a common engineering lexicon. 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.

The handbook could address generic guidelines on how to develop payload instrumentation with considerations and accommodations for jitter. A section in the handbook dealing with units and coordinate systems would be valuable. Such a handbook might identify preferred practices for performing standard checks of the structural FEMs, including checks/standards for generating optical sensitivities used for jitter analysis. Specifically identifying the necessary features for developing a 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, could be included in the Jitter Engineering Guidelines Handbook. However, a reduced-order state space model generated from the FEM, rather than the FEM itself, is actually used in jitter analysis. This makes the best practices for generating the state-space model from the FEM (e.g., frequency cutoff, model reduction, and residual vectors) an important subject to include in the Handbook.

Finding:

F-7 There is no generally accepted NASA engineering reference document with guidelines, lessons learned, and best practices for managing and mitigating spacecraft jitter.

Recommendation:

R-14 NASA, in partnership with its industry partners and other space Agencies, should initiate the development of a Jitter Engineering Guidelines Handbook documenting lessons learned and best practices for the analysis and testing needed for managing and mitigating spacecraft LoS jitter.

3.6 Application of MUFs

The application by GN&C engineers of MUFs has been common practice for decades. MUFs add conservatism to pre-launch predictions of jitter performance, typically before the flight system hardware is developed, assembled, integrated and tested on the ground. MUFs capture uncertainties in the structural models, disturbance forcing functions, and other areas of potential dynamic interaction (e.g., a servo-controlled instrument scanning mirror). While system models should naturally mature as the design and development process unfolds, leading to improved jitter prediction accuracy, the current state of system modelling for wide-spectrum vibration requires that MUF magnitudes be maintained at levels sufficient to protect against the under-prediction of vibration response.

Jitter analysts need heuristics like MUFs, but there is an attendant need to understand what data are behind the MUFs to know how and when to apply them properly as an integral part of the process of predicting ultimate levels of jitter and to determine how to meet jitter requirements. In fact, workshop participants felt strongly that a tutorial description of the proper applications of MUFs should be a subject covered in the envisioned Jitter Engineering Guidelines Handbook described in the preceding section.

Reference 6, the workshop presentation by Dr. Gary Henderson, provides a good description of MUFs and recommends several guidelines for their application. The magnitude of the MUFs applied vary over the course of a project's design and development phase. MUFs should change as the design matures, reduced as the fidelity of analysis and design definition improve between Preliminary Design Review and Critical Design Review, and then again after disturbance testing and system dynamic interaction testing is performed to anchor the system models.

Generally, the size of the MUFs used in jitter analysis will diminish as the flight system hardware matures. As the flight system model matures through the execution of component-level and subsystem-level testing and model correlation, the magnitude of the MUFs can decrease as uncertainty decreases and model confidence increases. This decrease in the MUF with increasing modelling details and test correlation is often referred to as MUF "burndown." The MUFs are frequency dependent, requiring higher magnitudes at higher frequencies given the reduction in fidelity and increased modal density of complex FEMs as frequency increases. It is common engineering practice to assume that the FEM of a space structure will have errors in the reported modal frequencies and mode shapes. The latter will lead to errors in the modal gain. Subject matter expertise judgment/experience should be employed to establish error bounds on the modal frequencies and the mode shapes. Even a test-correlated structural model may have model versus hardware frequency variability in "major modes" of ±5%, while preliminary models have much more variability.

MUFs account for amplitude variability and differences in modal gains and structural damping and should be applied according to the analysis method being used. Simple MUF multipliers are generally appropriate for analyzing broadband response. It should be recognized that preliminary structural models tend to use approximations, requiring the application of higher value MUFs. Flexible body modes with small modal participation, yet high LoS sensitivities, may have serious impacts, driving the need to perform relevant component level tests (e.g., mirror assembly frequency identification testing).[6]

The magnitude of MUFs, and the schedule for their reduction, will vary by project. The application of MUFs on a complex flagship-class multi-instrument mission like the James Webb Space Telescope (JWST), which necessitates a complex design to meet pointing/pointing stability requirements, will not be the same as that for a smaller, more rigid, and less complex spacecraft with a single fixed non-scanning payload instrument. As an example, Figure 3.6-1, referenced in Dr. Carl Blaurock's workshop presentation, defines one set of MUFs as a function of maturity (i.e., the degree of model verification by test) and by frequency range.[14] This particular set of example MUFs, published by Kevin O'Keefe, captures guidelines from a community of dynamics and controls SMEs.[15] From Figure 3.6-1, the largest MUF has a magnitude of 11.0 for the earliest analysis phase for the frequency range >200 Hz. That relatively large MUF value can be compared with the much lower MUF value of 3.0 that Figure 3.6-1 indicates should be used for the same frequency range >200 Hz with the most mature system model (i.e., the integrated and tested observatory system).

Workshop attendees felt that there is remaining work to be done in capturing structural damping uncertainty given that it can be reflected in a MUF or through use of a high Quality Factor (i.e., the dimensionless parameter Q) in the structural model. Conservatism in both areas can lead to excessive margins and an overdesigned system. It was reported at the workshop that the GN&C engineers at GSFC have often used a variation of the MUFs depicted in Figure 5 in their jitter prediction modelling work on NASA missions. At GSFC the 'MUFology' practice is typically to use a MUF as a multiplicative factor applied to the output predictions from the system model. The preferred implementation at GSFC uses a "signal chain" approach from disturbance inputs, through the flexible structure, to the payload instrument optical response outputs.[14]

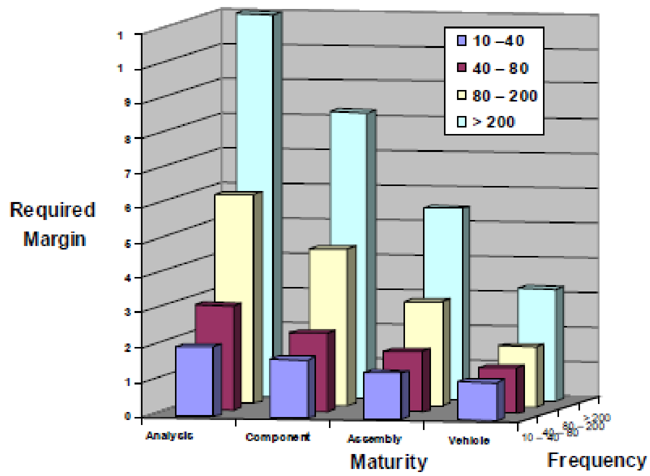

Figure 5. An example set of MUFs as a function of model maturity and frequency.[15]

Lastly, while workshop participants acknowledged that there is no single approach for applying MUFs that can be used universally for all flight projects, it was recognized there is a common imperative need for all flight projects to define, communicate, and enforce a consistent MUF policy early in the jitter modelling and analysis process. Inclusion of MUFs in the mission requirements documents has been suggested as a method to provide a consistent and level playing field especially when subsystems are built by various partners, sub-contractors, and/or vendors. Overly optimistic results will likely emerge if no MUF, or an unrealistically low MUF, is used to generate early jitter performance predictions. Conversely, as described in Reference 16, the lack of a clear and consistent MUF policy could lead to inconsistent application and stacking of MUFs potentially resulting in over conservative predictions of jitter performance. This could result in the flight project considering jitter mitigations that are impractical, and most importantly, not required.[16]

<u>Findings:</u>

F-8 MUFs add conservatism to pre-launch predictions of jitter performance, before the flight system hardware is integrated/tested on the ground.

F-9 Spacecraft engineering organizations and flight project teams often do not have well defined, established, and consistent MUF policies to use at the start of the jitter modelling and analysis effort which can lead to inconsistent application and stacking of MUFs potentially resulting in over conservative jitter performance predictions.

Recommendations:

R-15 NASA should consider methods to codify or standardize a preferred approach to determining, applying, and updating MUFs by project phase and spacecraft classification. In such a standardized approach, the MUFs should be refined as design matures only after testing is completed and updates are included in the analysis model. The preferred approach should be documented by NASA in the Jitter Engineering Guidelines Handbook.

R-16 In conjunction with their stakeholders, each flight project should define, establish and enforce, early on in the jitter engineering process, a consistent policy for applying MUFs.

R-17 Projects should include MUFs, and how they evolve throughout the project lifecycle, in the mission requirements documents.

3.7 Consideration of Streamlined/Tailored Approaches for Non-Flagship Missions

The majority of the discussion at the workshop focused on ways to manage and mitigate jitter for flagship-class missions where there are relatively large teams and resources available to solve the jitter problem. Typically, the comprehensive jitter solutions for flagship-class observatories, which are generally bespoke, "one of a kind", physically large multi-instrument observatories (e.g., JWST) are highly customized mission-unique designs that employ extensive modelling, analysis, and test, which is costly and time consuming.

Since the workshop, an emergent topic has come to the attention of the community: what is the nature of an affordable jitter solution for non-flagship missions that use 'commercial class' small spacecraft? This class of missions includes continued launches of commercial constellations for Earth observation, communications, or broadband internet service; proliferated low Earth orbit (LEO) spacecraft constellations for DoD; and science mission architectures studied by NASA with numerous spacecraft flying in formation. Some missions in this class may still need relatively high performance at a fraction of the cost of heritage systems with similar performance. Constellations may have hundreds if not thousands of spacecraft, some of which will no doubt need some form of solution for jitter-sensitive payloads like optical communications terminals used for crosslink networking between multiple platforms in LEO. This is non-trivial since the LoS pointing stability requirement required to maintain optical communication crosslinks can be less than 100 nano-radians. Optical communications terminals for spacecraft in this class should be designed with slightly larger beam widths and/or higher power levels than existing systems to ensure robust pointing/pointing stability performance in the presence of the noisier 'commercial-class' spacecraft bus disturbance environment.

All this will drive the need for a paradigm shift to create a lower-cost jitter mitigation process. Industry will need to perform cost/benefit trades to determine a streamlined approach to accomplishing cost-effective jitter solutions on non-flagship missions, with only minimal non-recurrent engineering required. These tailored jitter solutions will need to be extensible, flexible, and implementable in a high-volume production environment. One way for industry to address this situation is to adopt of a 'Design for Jitter' approach by baselining a minimum set of jitter mitigating features. For example, the universal inclusion of a passive mechanical isolation layer, tunable before launch, as a quieting interface between the commercial-class bus and the optical payload may be an effective design approach that could be cost-efficient if designed to be modular and available at low unit cost. Another example approach to reducing non-recurring engineering: instead of testing and characterizing reaction wheels for each individual spacecraft as is typically done for flagship-class missions, that testing could be done on a single unit to establish baseline performance for the entire constellation.

Findings:

F-10 There is a need for the community to determine an acceptable streamlined/tailored jitter solution for non-flagship 'commercial-class' spacecraft.

Recommendations:

R-18 Define the characteristics and features of a "Design for Jitter" approach for 'commercial-class' spacecraft.

4.0 Summary and Go Forward Plans

The workshop held in October 2019 revealed a community of SMEs eager to share their knowledge and help prepare for the future. The Workshop generated findings and recommendations, listed throughout Section 3, which are listed for easy reference in Appendix 1. The core team that planned the workshop has assessed this set of recommendations and prioritized them for future action. Many of the recommendations will require a long-term strategy and resources to implement.

Two particular recommendations have emerged as high-priority actions that can be directly pursued in the immediate future. The first is the development of a Jitter Engineering Guidelines Handbook. The second is to plan and to hold a second, possibly inter-Agency, face-to-face Spacecraft LoS Jitter Workshop, hosted by NASA or ESA in the near future, perhaps as early as late 2021. This should maintain momentum to accomplish some high-priority goals for the community. Obviously, the desire to hold this second workshop as a face-to-face meeting will be subject to the constraints imposed by the on-going COVID-19 pandemic. If pandemic considerations prohibit a face-to-face meeting, an alternative virtual workshop will be the fallback option rather than waiting indefinitely to gather in person again. It is envisioned that a portion of the second, multi-day, jitter workshop would be allocated for interactive hands-on work on the Jitter Engineering Guidelines Handbook. A supporting action will be to form a few small and focused Jitter Working Groups to create and execute a plan for following up with the recommendations listed above and to perform specific tasks. These Working Groups would conduct work on their individual tasks and then meet at continuing jitter workshops to report out to the community on their progress.

5.0 References

1 Dennehy, Cornelius J. and Aron A. Wolf, Aron A., NASA Engineering & Safety Center (NESC) Spacecraft Line-of-Sight (LoS) Jitter Workshop: Introductory Remarks, 23 October 2019.

2 Dennehy, Cornelius J. and Alvarez-Salazar, Oscar S., "Spacecraft Micro-Vibration: A Survey of Problems, Experiences, Potential Solutions, and Some Lessons Learned," *European Conference on Spacecraft Structures, Materials & Environmental Testing*,

(ECSSMET2018), ESA/ESTEC, Noordwijk, The Netherlands, 28 May through 1 June 2018 (also published as NASA TM−2018-220075, July 2018).

3 European Space Agency, European Cooperation for Space Standardization (ESA ECSS) (2012), Section 13.3 Micro-vibrations, Space Engineering: Spacecraft Mechanical Loads Analysis Handbook, ECSS-E-HB-32-26.

4 Blackmore, Lars, et al, "Instrument Pointing Capabilities: Past, Present and Future," *34th Annual American Astronautical Society (AAS) Guidance, Navigation, and Control Conference*, AAS Paper 11-091 paper, Breckenridge, Colorado, February 2011

5 Dennehy, Cornelius J., "A Survey of Reaction Wheel Disturbance Modeling Approaches For Spacecraft Line-Of-Sight Jitter Performance Analysis," *18th European Space Mechanisms and Tribology Symposium (ESMATS 2019)*, Munich, Germany, 18–20 September 2019

6 Henderson, Gary, "Managing Observatory Line-of-Sight Jitter (with an emphasis on micro-vibrations), A "Jitter 101" Process Overview," Aerospace Corporation, 30 January 2019.

7 Lucke, R. L., Sirlin, S. W., and San Martin, A. M., "New Definitions of Pointing Stability: AC and DC Effects," *Journal of the Astronautical Sciences*, Vol. 40, No. 4, Oct.–Dec. 1992, pp. 557–576.

8 Pittelkau, M. E., *Pointing Error Definitions, Metrics, and Algorithms, American Astronautical Society*, AAS 03-559, p. 901, 2003.

9 Pittelkau, M. E. and McKinley, W. G., "Pointing Error Metrics: Displacement, Smear, Jitter, and Sitter with Application to Image Motion MTF," in *AIAA Guidance, Navigation, and Control Conf.*, 13–16 Aug 2012, Minneapolis, MN, p. 19, Paper No. AIAA-2012-4869.

10 Bayard, D. S., "A State-Space Approach to Computing Spacecraft Pointing Jitter," *AIAA J. Guidance Control Dyn., Vol.* **27**, No. 3, May-June, 2004, 426–433,

11 Pittelkau, M. E. and McKinley, W. G., "Optical Transfer Functions, Weighting Functions, and Metrics for Images with Two-Dimensional Line-of-Sight Motion," *Optical Engineering* Vol. 55, No. 6, June 2016.

12 John Sudey, Jr., Michael Hagopian, and Cornelius Dennehy "GOES I-M: A Retrospective Look at INR and Jitter and Lessons Learned," *42nd Annual American Astronautical Society (AAS) Guidance, Navigation, and Control Conference*, AAS Paper 19-132, February 2019

13 Hagopian, Michael, "Jitter Experiences: Predicting, Managing, Controlling, and Testing Spacecraft Jitter," Adnet Systems, Inc., 23 October 2019

14 Blaurock, Carl, Jitter Experience and EllipTool®, 19 October 2019

15 O'Keefe, K., "Dynamic Modeling Methodology," *2011 International Conference on Space Optical Systems and Applications*, Santa Monica, California, May 2011.

16 Smith, Brett A., Sirlin, Sam, and Seubert, Carl, "Europa Clipper Pointing Stability: Challenges on A Multi-Instrument Mission to Jupiter," *42nd Annual American Astronautical Society (AAS) Guidance, Navigation, and Control Conference*, AAS Paper 19-136, February 2019.

Appendix 1. Summary List of Jitter Workshop Findings and Recommendations

Findings

F-1 There are multiple, similar but not identical, definitions of jitter and associated terms in use across the jitter engineering community.

F-2 Managing jitter is a highly multidisciplinary systems-oriented task, requiring involvement of an experienced multidisciplinary team, particularly for more demanding spacecraft jitter requirements (e.g., at the nano-radian or pico-radian level).

F-3 Jitter management/mitigation should be addressed in the early project phases when many impactful system architectural decisions are most often made.

F-4 Sources of uncertainty should be well understood and driven down as the design matures.

F-5 Most gross errors are caused by confusion or misunderstandings of units (e.g., confusion between nano-radians and milli-arcsecond units of angular measure) or lack of discipline regarding coordinate systems.

F-6 There is an imperative need for GN&C engineers to obtain and analyze in-flight jitter related data to allow for in-flight system jitter performance improvements and to validate pre-launch models to support future missions.

F-7 There is no generally accepted NASA engineering reference document with guidelines, lessons learned, and best practices for managing and mitigating spacecraft jitter.

F-8 MUFs add conservatism to pre-launch predictions of jitter performance, before the flight system hardware is integrated/tested on the ground.

F-9 Spacecraft engineering organizations and flight project teams often do not have well defined, established, and consistent MUF policies to use at the start of the jitter modelling and analysis effort which can lead to inconsistent application and stacking of MUFs potentially resulting in over conservative jitter performance predictions.

F-10 There is a need for the community to determine an acceptable streamlined/tailored jitter solution for non-flagship ‘commercial-class’ spacecraft.

Recommendations

R-1 NASA and ESA should coordinate on planning and executing a second face-to-face inter-Agency Spacecraft LoS Jitter Workshop as soon as practical.

R-2 NASA to consider forming Jitter Workshop Working Groups to perform specific jitter related tasks (e.g., the development of Jitter Engineering Guidelines Handbook), which would seek inputs from across organizations and provide progress updates at future Spacecraft LoS Jitter Workshops.

R-3 A flight project’s jitter engineering team should establish a strong working relationship with stakeholders (e.g., scientists planning Earth and Space science missions) where LoS jitter considerations are paramount.

R-4 Standardize an approach (e.g., Reference 11) as the basis for engineers and scientists to communicate concerning instrument jitter requirements and performance metrics.

R-5 Converge on common jitter terminology, which can be documented in the Jitter Engineering Guidelines Handbook.

R-6 Create and maintain an experienced, multidisciplinary team to manage jitter throughout the project lifecycle.

R-7 Carefully consider jitter management and mitigation during the mission formulation phase, including the planning for early test campaigns and developing the capability for performing integrated modelling, simulation, and analyses focused on the areas of greatest jitter uncertainty.

R-8 To optimize the whole system, excessive conservatism should be avoided in the design and requirements definition process, and margins should be assessed at the system level to avoid too many layers of margin across component providers.

R-9 Requirements should be specified in terms of system end-to-end versus interface performance.

R-10 Systems engineering must be aware of potential conflicts of interest, e.g., when one participant is holding excessive conservatism for their hardware to control their own risk vs. a more integrated program approach.

R-11 In the modelling, simulation, and analysis pay careful attention to units and coordinate systems.

R-12 Include science team and ground system team members responsible for the post-processing of instrument data (to remove jitter artefacts) in discussions of jitter management and mitigations.

R-13 NASA, in partnership with its industry partners and other space Agencies, should initiate an investigative trade study into miniaturized jitter measurement instrumentation alternatives.

R-14 NASA, in partnership with its industry partners and other space Agencies, should initiate the development of a Jitter Engineering Guidelines Handbook documenting lessons learned and best practices for the analysis and testing needed for managing and mitigating spacecraft LoS jitter.

R-15 NASA should consider methods to codify or standardize a preferred approach to determining, applying, and updating MUFs by project phase and spacecraft classification. In such a standardized approach, the MUFs should be refined as design matures only after testing is completed and updates are included in the analysis model. The preferred approach should be documented by NASA in the Jitter Engineering Guidelines Handbook.

R-16 In conjunction with their stakeholders, each flight project should define, establish and enforce, early on in the jitter engineering process, a consistent policy for applying MUFs.

R-17 Projects should include MUFs, and how they evolve throughout the project lifecycle, in the mission requirements documents.

R-18 Define the characteristics and features of a “Design for Jitter” approach for ‘commercial-class’ spacecraft.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
06/23/2021

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Spacecraft Line-of-Sight Jitter Management and Mitigation Lessons Learned and Engineering Best Practices

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Dennehy, Cornelius J.; Wolf, Aron A.; Swanson, Davin K.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
869021.01.23.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-20210017871

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category Space Transportation and Safety
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
For the guidance, navigation, and control community of practice needs to leverage collective experiences and document their best practices and lessons learned to address future micro-vibration challenges, the NASA Engineering & Safety Center sponsored a 2-day Spacecraft LoS Jitter Workshop in late 2019. The workshop's goal was to provide a multidisciplinary forum to elicit deeper understanding of the issues related to addressing the spacecraft LoS jitter/micro-vibration problem. Representatives from NASA, ESA, NASA's industrial partners, etc. participated in the workshop. This paper describes the motivation for the workshop and summarize the identified findings and recommendations.

15. SUBJECT TERMS
Lessons Learned; NASA Engineering and Safety Center; Line of Site; Guidance Navigation and Control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	30	(443) 757-5802