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NASA Space Observatory Precision Pointing Benchmark Problem Development

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Acknowledgments

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NASA Engineering and Safety Center (NESC)
Technical Assessment Report

NASA Space Observatory Precision Pointing
Benchmark Problem Development
TI-22-01785

Tannen VanZwieten, Associate Principal Engineer, KSC

Technical Lead

NRB approval date: March 7, 2024

Report Approval and Revision History

NOTE: This document was approved at the March 7, 2024, NRB.

Approved: Timmy Wilson	Digitally signed by Timmy Wilson Date: 2024.04.16 16:41:39 -04'00'
NESC Director	

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Tannen VanZwieten, Associate Principal Engineer, KSC	March 7, 2024

Table of Contents

List of Figures

List of Tables

Technical Assessment Report

1.0 Notification and Authorization

An interagency workshop in May 2021 on guidance, navigation, and control (GNC) verification and validation (V&V) methods and techniques identified needs for the formulation and public release of relevant V&V benchmark problems as a practical way forward for the discipline. A decision was made by the NASA Technical Fellow for GNC and the NASA Engineering and Safety Center (NESC) GNC Technical Discipline Team (TDT) to produce a benchmark problem focusing on the problem of space observatory precision pointing. Several engineering benchmark problems developed since the late 1980s have been shown to be a useful means to study solutions to common, standardized space observatory GNC challenges.

The space observatory benchmark problem discussed in this report builds on prior benchmark problems to investigate the concept of operations for observations, satisfying stringent jitter requirements while demonstrating aggressive attitude agility, and remaining within controller stability margins, and meeting robustness requirements. The second generation—Generation II (Gen II)—space observatory benchmark problem developed here provides an established, easily accessible, standard framework for the GNC community of practice to compare and contrast alternative solutions to this important space system engineering challenge. This will be a platform for the GNC community within government, academia, and industry to develop an innovative disturbance rejection solution and line-of-sight (LOS) pointing capability to demonstrate what is achievable in this challenging space mission.

The work was performed in two phases. In Phase I, the problem was scoped, and the fundamental architecture and nature of this problem was defined. In Phase II, a detailed design was developed of the space observatory pointing benchmark problem.

2.0 Signatures

Submitted by: NESC Lead

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Dr. Tannen VanZwieten

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Dr. Christopher D'Souza	Mr. Cornelius J. Dennehy

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team Members

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3.1 Acknowledgements

The NESC assessment team would like to thank Tom Battista of The Aerospace Corporation for his contribution in Phase I of this activity. The team would also like to thank Steve Gentz, Peter Seiler, Eric Stoneking, James O'Donnell, Steve Rickman, Chris Broadway, Joel Sills, Heather Koehler, Peter Panetta, John Wall, and Dan Yuchnovicz for peer reviewing this NESC final report.

4.0 Executive Summary

An interagency workshop in May 2021 on guidance, navigation, and control (GNC) verification and validation (V&V) methods and techniques identified needs for the formulation and public release of relevant V&V benchmark problems as a practical way forward for the discipline [ref. 1]. Such benchmark problems would be shared across the GNC community of practice to allow for comparison of alternative solutions and associated methodologies.

Consequently, a decision was made by the NASA Technical Fellow for GNC and the NASA Engineering and Safety Center (NESC) GNC Technical Discipline Team (TDT) to produce a benchmark problem focusing on the problem of space observatory precision pointing. The Space Observatory Precision Pointing problem was selected as the subject of this first GNC benchmark problem development given that the design of the pointing control system for modern space observatories remains a significant technical challenge to NASA and its industry partners. Further, this particular subject area has a strong alignment with parallel NESC GNC TDT efforts to develop an optical pointing error metrics MATLAB® toolbox and create an engineering handbook for space observatory jitter analysis and test. Thirdly, it was believed that previous work done decades ago to develop related benchmark problems could be leveraged.

Since the mid-1980s, NASA has launched several first-generation interplanetary observatory spacecraft. A salient feature of these missions has been the mounting of the optical instrument payload on top of a large flexible space structure. This observatory configuration results in challenging control-structure interaction (CSI) problems that have been studied over several decades. The December 2021 launch of the James Webb Space Telescope marked the latest example of such a mission.

One way to encourage development of novel pointing control methods is to provide a benchmark problem for researchers. By the mid-2000s, the control community developed a few well-known benchmark problems with a focus on CSI applications, referred to herein as Generation (Gen) I CSI problems [ref. 2-9]. However, over the past 15 years, the control challenges in space observatory optical observation missions have shifted from CSI to line-of-sight (LOS) precision pointing. This is because popular designs of the Gen II space observatory mission have eliminated the large structure interface by mounting the optical payload directly on top of a relatively rigid spacecraft bus platform. Thus, the community's primary engineering challenge now focuses on achieving accurate LOS pointing at the payload level, with maximum rejection of the underlying disturbances.

The NESC, in collaboration with the The Aerospace Corporation, has developed a benchmark problem to study the challenging control issues encountered by Gen II space observatories. This benchmark problem is directed at potential government, academic, and industry researchers to design a set of innovative payload control laws with the maximal optical disturbance rejection (ODR) capability to meet a set of microradian (μrad)-level LOS jitter requirements. This report describes the development of such a benchmark problem. An integrated LOS plant model and disturbance/command profiles are provided for users to analyze their design and simulation, with a user guide [ref. 15] describing the software inputs/outputs.

A Gen II Space Observatory benchmark problem is defined and described in this report. The user's primary design objective is to synthesize a payload LOS pointing controller, using any design methodology the user selects that can meet stability, robustness, and pointing performance while rejecting disturbances. In addition, the user must design a bus controller to stabilize the base body. A satisfactory design will meet smear and jitter requirements while simultaneously maintaining the optical payload command following. The payload-slewing commands are arbitrarily defined, and internal/external disturbances are derived from public domain references [refs. 8-9].

In summary, a new benchmark problem for the precision pointing of a space observatory (e.g., a space telescope) has been formulated. The team has worked to ensure the problem is realistic, representative, and challenging enough to inspire government, academic, and industry researchers to create innovative, and perhaps non-traditional and/or alternative, design solutions. The team believes the benchmark problem put forward herein is conducive to many of the types of control strategies that users can potentially apply. Classical linear time invariant (LTI) controllers, which are relatively easy to verify, are expected as potential user solutions. However, the team believes it is unlikely that such LTI controllers can meet all the benchmark requirements.

It is anticipated this new benchmark problem will provide a common framework for researchers to explore and investigate various advanced control techniques that the aerospace industrial community has been hesitant to employ due to a perception of higher risk and/or unfamiliarity. While academic researchers are familiar with advanced control techniques, unfortunately many do not have access to recognized high-fidelity benchmark problems. This benchmark problem therefore can serve as a bridge between the academic and industrial communities.

It is believed that going forward this benchmark problem could have a significant influence on the field by providing an opportunity for users to experiment with solutions based on neural networks, H^{∞}, adaptive methods, machine learning, model predictive control, online convex optimization, and other modern, novel, and evolving techniques. These are techniques that have been studied by researchers but have not traditionally been applied to NASA's operational spacecraft. It must be considered that these advanced techniques, while offering the promise of improved performance, pose fundamental stability and robustness verification challenges that need to be addressed. Thus, a critical and necessary part of a complete and comprehensive user response to this new benchmark problem will be the demonstration of an appropriate and satisfactory methodology for the verification of the proposed design solution's stability and robustness properties.

A user guide has been developed. It describes the benchmark problem software functionality and inputs/outputs. The MathWorks MATLAB® files representing the benchmark problem will need to be submitted through the NASA Software Release System (SRS) process for approval prior to public release.

The NESC GNC TDT is planning to roll out this benchmark problem to the community of practice in the near future. The benchmark problem software must first be submitted to the NASA SRS to obtain formal approval for its public release. The rollout plan for releasing this benchmark problem is envisioned to start internally within NASA and subsequently include sharing the problem with NASA's academic and industry partners once formal approval has been obtained for public release.

Lastly, The Aerospace Corporation has raised the possibility of performing some level of hardware-in-the-loop (HITL) verification testing of the most innovative control algorithms that users develop. The logistical details would need to be negotiated, and it is not clear the NESC would play a role as this potential follow-on work is outside the scope of this assessment.

5.0 Assessment Scope

This is discipline-advancing work, intended to identify unique solutions for missions requiring precision pointing of a space observatory's payload instruments. This NESC assessment focused on architecting and implementing a fully formed benchmark problem with adequate documentation to encourage the broad study of solutions to the technical challenge of precision pointing of a space observatory. The problem is constructed as an open-source problem, flexible enough in its architecture to be useful in the study of many space observatory configurations and applications.

The assessment included detailed modeling and simulation development and the necessary work to perform benchmark problem model verification. In particular, the space observatory model consisted of a bus and steerable optical payload; baseline attitude controllers for the spacecraft bus; uncertainties, including variable mass properties and variable flexible-body dynamics variations; and adaptations for degraded sensors and actuators. Provisions for fault or failure modes of operation were not included. In addition, the benchmark problem architecture has a built-in capability to generate and evaluate standard parameters for jitter analysis using the pointing error metrics developed over the past decade by Dr. Mark Pittelkau and his colleagues [ref. 14].

Note that in an effort parallel to the development of this benchmark problem the NESC GNC TDT sponsored development of an Image Motion Optical Transfer Function and Pointing Performance Analysis Toolbox (based in MathWorks MATLAB®). This toolbox was developed by Dr. Peter Seiler[1] in close collaboration with Dr. Mark Pittelkau. This toolbox incorporates all of the Pittelkau-developed pointing error metrics, which are rapidly becoming an industry standard. This toolbox provides a set of software tools to aid in image motion and pointing performance analysis to verify optical payload imaging and pointing performance for spacecraft carrying optical payloads. The pointing performance analysis methodology supports the pointing control system design process and produces data required for the image motion optical performance analysis. The development of this toolbox has been completed, including a comprehensive user guide. The toolbox/user guide has been entered into the formal NASA SRS. Once the approval for public release of the toolbox software has been granted, this jitter analysis toolbox may be provided by the NESC GNC TDT upon request.

This work included implementing plans for benchmark problem open-source rollout/ release to the government, academic, and industry GNC community of practice in a manner that makes it most accessible to the community. A benchmark problem user guide [ref. 15] and a technical paper and a technical presentation [refs. 20 and 21] describing the benchmark problem were published to inform the GNC community of practice.

6.0 Problem Description and Background

The design of the pointing control system for modern space observatories, typically large-aperture, lightweight-structure platforms, with precision payload optical instrument pointing stability and control, remains a significant technical challenge to NASA and government,

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[1] Dr. Seiler is an Associate Professor in the Electrical Engineering and Computer Science Department at the University of Michigan. He has extensive experience in developing controls engineering toolboxes using MATLAB®.

academic, and industry organizations. The pointing dynamics and control of space observatories are much more challenging and complicated than the normal spacecraft bus vehicle attitude control system design. Among the aspects involved: large-space-structure-driven dynamics and control; precision optical payload pointing; pointing performance metrics; payload dynamics modeling; disturbance rejection; passive and/or active disturbance isolation (passive and/or active); jitter analysis; flexible body dynamics; propellant slosh dynamics; attitude knowledge; system identification; LOS geometry; calibration; decoupling dynamics; fast slewing; reaction-wheel friction compensation and friction estimator design; and multi-model, non-colocated control law design.

Several engineering benchmark problems have been developed since the late 1980s, and these have been a useful means of studying various ways to solve a common, standardized reference problem [refs. 2-9]. There is no single consolidated reference summarizing the extensive work performed to solve the CSI problem in the 1990s; the references cited here are only a small but highly representative example of the vast amount of technical literature from the 1990s centered around the study of advanced methods and techniques to control lightweight and flexible large-space structures; those applications are referred to as the Gen I CSI problem in this report. The purpose of this report is to introduce a technically well-defined and easily accessible Gen II precision pointing space observatory benchmark problem that will provide the GNC community of practice with a standard framework with which to compare and contrast alternative solutions to this important space system engineering challenge. A Gen II benchmark space observatory problem will be a suitable platform for the GNC academic and industry communities to provide their innovative ODR solution. Users will be asked to demonstrate the “art of the possible” in exquisite (i.e., µrad level) LOS pointing via this challenging benchmark problem. Figure 1 illustrates the control loop closures in Gen I versus Gen II.

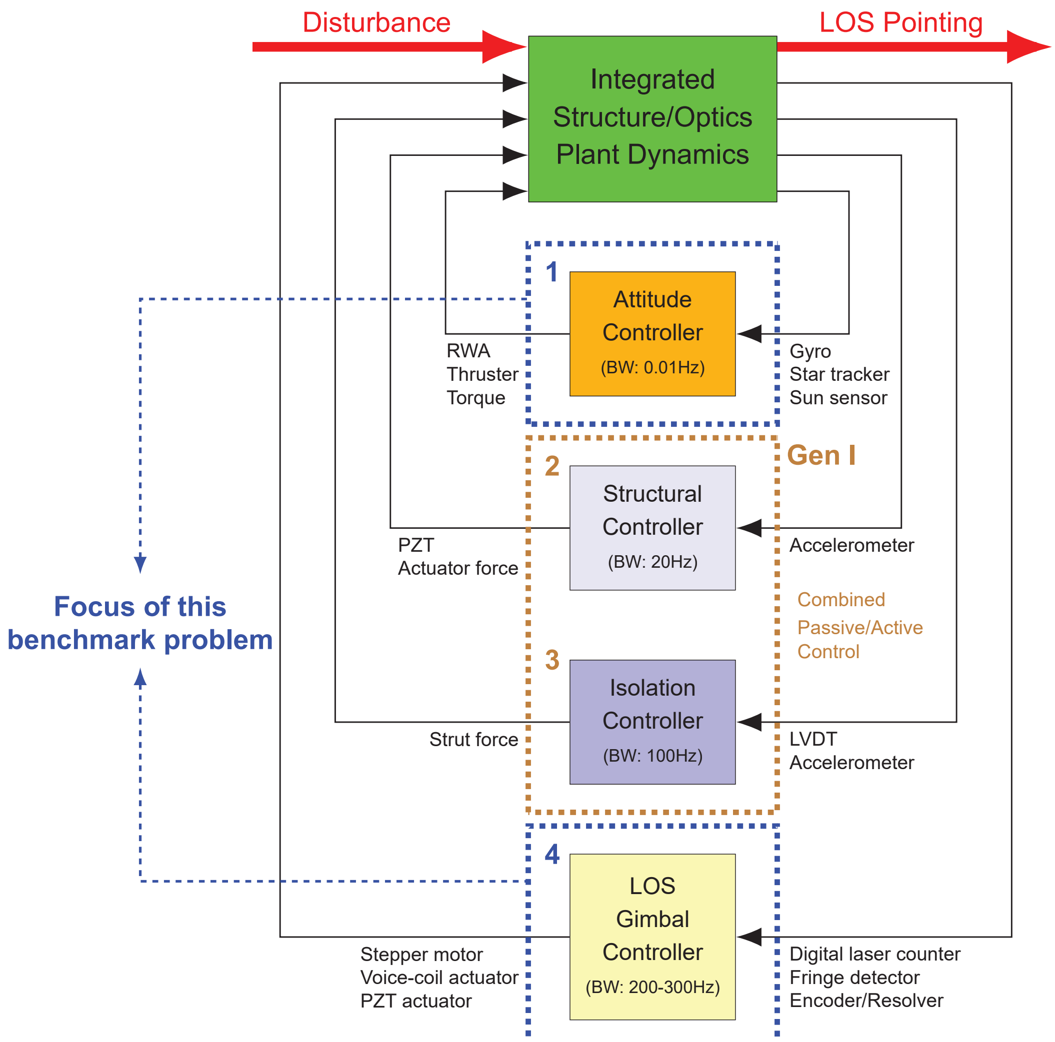

Figure 1. Multi-Layer Active Optical/Structure Control System[2]

While Gen I CSI problems have been focused on building Layers 2 and 3 to suppress the structure vibrations, the Gen II ODR problem that is the subject of this benchmark problem focuses on the development of Layer 4 to maximize the optical payload disturbance rejection capability. Layer 1 is a bus controller design to stabilize the base body spacecraft bus element of the space observatory.

Table 1 illustrates a summary of control design approaches developed in Gen I CSI missions versus the Gen II ODR focus.

[2] Note that in Figure 1 the acronym BW stands for bandwidth, the acronym PZT stands for piezoelectric transducer (actuator), the acronym LVDT stands for linear variable differential transformer, and the acronym RWA stands for reaction wheel assembly.

Table 1. Control Design Approaches: Gen I versus Gen II

Gen I - Well Established CSI Problem (Layers 2–3)

Benchmark Problem			Layer 1 (BUS Control)	Layer 2 (Structure Control)	Layer 3 (Isolation Control)	Layer4 (LOS Control)	Notes
Gen I (CSI)	1	JOSE (1985-1988) [Ref. 5]		Collocated Rate Feedback		H-infinity	* Large space structure * Study of structure/LOS control
	2	CSI Phase A (1991-1993) [Ref. 4]		Non-Collocated H-infinity			* Large space structure * Study of structure control
	3	CSI Phase B (1993- 1996) [Ref. 6-7]		Non-Collocated H-infinity	Passive/Active spring/damper	H-infinity	* Large space structure * Full study of LOS disturbance rejection
	4	CSI MPI Testbed (1996-1999) [Ref. 7-9]		Non-Collocated H-infinity	Passive/Active Spring/Damper	H-infinity	* Large space structure * Full study of LOS disturbance rejection
	5	Two-Mass-Spring (1991-1992) [Ref. 3]		Non-Collocated H-infinity			* Focus on structural uncertainty/robustness and known periodic disturbance
Gen II (ODR)	6	Defense/Science Missions (1970's -present)	Classical Controller		Passive Spring/Damper	Classical/ H-infinity Controller	* With gyro feedforward disturbance rejection scheme
	7	Spacecraft with Optical Payload (2023 and beyond)	Classical Controller			Gen II Benchmark Problem	* Study of disturbance rejection methodology

Gen II Benchmark Problem Focus on Layer 4

7.0 Technical Work

7.1 Gen II Benchmark Problem

As a GNC discipline advancing effort, the principal purpose of developing this benchmark is to provide a common reference problem that will build the GNC community's expertise in robust LOS control algorithms for optical payloads. The user will need to design both a bus controller to stabilize the underlying spacecraft attitude as well as a payload LOS controller. The design of the payload LOS controller will be the most demanding aspect of solving the benchmark problem. Typically, the dynamics and control of payload pointing are more challenging and complicated than the spacecraft bus attitude dynamics and control. In general, the design of the bus controller is viewed within the community as essentially a "solved problem" and is anticipated to be fairly straightforward.

In developing solutions to the benchmark problem, users can employ any control design methodology[3] but are encouraged to consider exploiting the Robust Control Toolbox from MathWorks, which provides functions and blocks for analyzing and tuning control systems for performance and robustness in the presence of plant uncertainties [ref. 12].

[3] Examples of control methodologies users could employ include the following: neural networks, H^{∞}, adaptive methods, machine learning, model predictive control, on-line convex optimization, and other modern, novel, and evolving techniques.

The user will only be able to drive the payload's optical LOS vector by controlling a two-axis fast-steering mirror (FSM), which uses the FSM mirror encoders, a payload gyro, and payload star tracker measurements. FSMs have a wide range of applications and are commonly found in high-performance optical systems, especially for LOS control applications. Simply put, an FSM is a high-bandwidth (e.g., 200 to 300 Hz) physical mechanism composed of a reflective mirror, a pair of motion-tracking encoder sensors, a displacement actuator (e.g., a gimbal), and a processing unit that aid in receiving an incoming optical beam at the correct angle or redirecting a beam in a specific direction. The LOS vector must be stabilized during optical sensor integration windows to meet jitter, smear, and displacement requirements in the presence of typical mission-like spacecraft disturbances.

The user may design feedback and/or feedforward control laws to reject the internal/external disturbances from the environment with required stability margins, robustness, and pointing performance.[4] The specific stability margin, robustness, and pointing performance requirements associated with this benchmark problem that must be satisfied by the user are provided in Section 7.6. These specific jitter, smear, and displacement requirements are defined in such a way that they cannot be met without the user designing an active disturbance rejection scheme as a solution to the benchmark problem. The detailed definition of the terms *jitter*, *smear*, and *displacement* are given in reference 14.

Sections 7.2 through 7.5 discuss the spacecraft model; mapping of LOS from the two-axis FSM gimbal to Earth-Centered Inertial (ECI) frame; the command profiles; and the external/internal payload disturbances. These important benchmark problem data will be made available to the user in a MathWorks MATLAB® file format. No specific design/simulation tools or platform is required to do the design and/or analysis.

7.2 Plant Model — Space Observatory

The spacecraft model consists of rigid bodies connected by springs, with spring constants tuned to give desired system modal frequencies. The model includes a bus, two solar arrays, and a payload. Mode shape coefficients are provided (in a text file) along with a simple MathWorks MATLAB® script to construct a continuous state space model for stability analysis and LOS jitter analysis. Any non-MATLAB® users may employ the simple text file containing the final state-space matrices of the spacecraft/payload dynamic model.

The bus consists of a single rigid body. There are grid points for reaction wheel disturbance force and torque inputs, reaction wheel spin axis torque inputs, bus orientation outputs (i.e., star tracker attitude), and bus gyroscope rate outputs.

Each solar array consists of four rigid panels, with one torsional spring between each panel (along the panel edges) and three torsional springs connecting the first panel to the bus. Springs are tuned to give the first fixed base solar array bending mode at approximately 1.0 Hz, and a solar array torsional mode at approximately 1.5 Hz.

The payload consists of a double-gimballed rigid secondary fast steering mirror connected to a rigid optical bench. The focal plane and primary mirror are rigidly connected to the payload's

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[4] The definitions of the fundamental control theory terms *stability margin*, *robustness*, and *pointing performance* can be found in Åström, KJ, and Murray, R, "Feedback Systems: An Introduction for Scientists and Engineers, 2nd Ed.," Princeton University Press, 2021.

optical bench. There is a 2.0-Hz flexure spring about each gimbal axis. The payload is connected to the bus with three translational and three torsional springs. Springs are tuned to give payload rotational modes at approximately 50 to 80 Hz and translational modes at approximately 30 to 60 Hz. There are grid points for gimbal torque inputs, cryocooler disturbance torque inputs, gimbal angle outputs, and payload gyroscope rate outputs.

The decision was made to limit the mechanical disturbance sources to reaction wheels and the cryocooler. Consideration was initially given to including the solar array drive mechanisms and possibly the antenna gimbal drive mechanisms, but these were ultimately not included in the space observatory model given their low-frequency nature and the fact that in realistic science observing modes of operation these mechanisms would typically not be in use.

The system model includes a LOS error output (X/Y angles, with nominal LOS along the Z-axis when gimbal angles are zero) based on commanded versus truth bus attitude, commanded versus truth gimbal angles, and flex motion (i.e., payload angles are relative to the bus). Detailed coordinate system and model input/output definitions are described in the user guide [ref. 15].

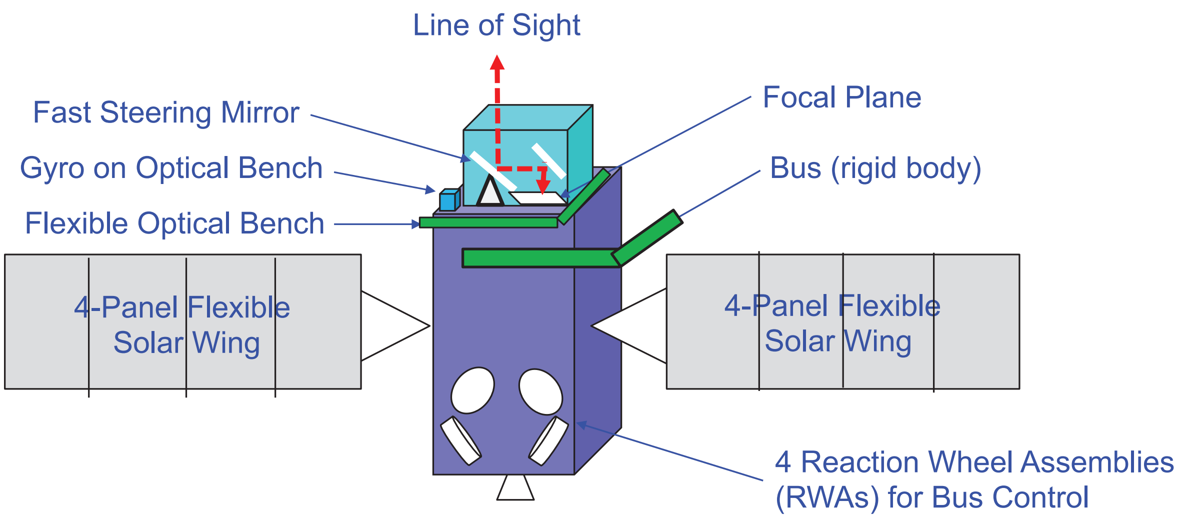

Figure 2. Notional Space Observatory

7.3 Focal Plane Vector Mapping to LOS in ECI Frame

The LOS optical path is modeled with two mirrors, as shown in Figure 3. The LOS in free space reflects off a gimbaled secondary fast steering mirror, passes through intermediate optics (not modeled here), reflects off a fixed primary mirror, and is directed to the focal plane to create an image. The LOS is affected by FSM gimbal motion, payload motion relative to the bus (due to flexibility), and bus motion relative to inertial space.

High-fidelity actuator/sensor dynamics are not necessary to include in this benchmark problem because they do not influence the fundamental controller design solution. Instead, they may increase the simulation complexity and result in long execution times and hence longer design iterations. However, in the future, it might be necessary/desired to include the high-fidelity sensor and actuator dynamics for some specific "full up" verification runs after an initial design has been completed. It is envisioned that this additional work could be done on a limited set of innovative design solutions emerging from the GNC community of practice.

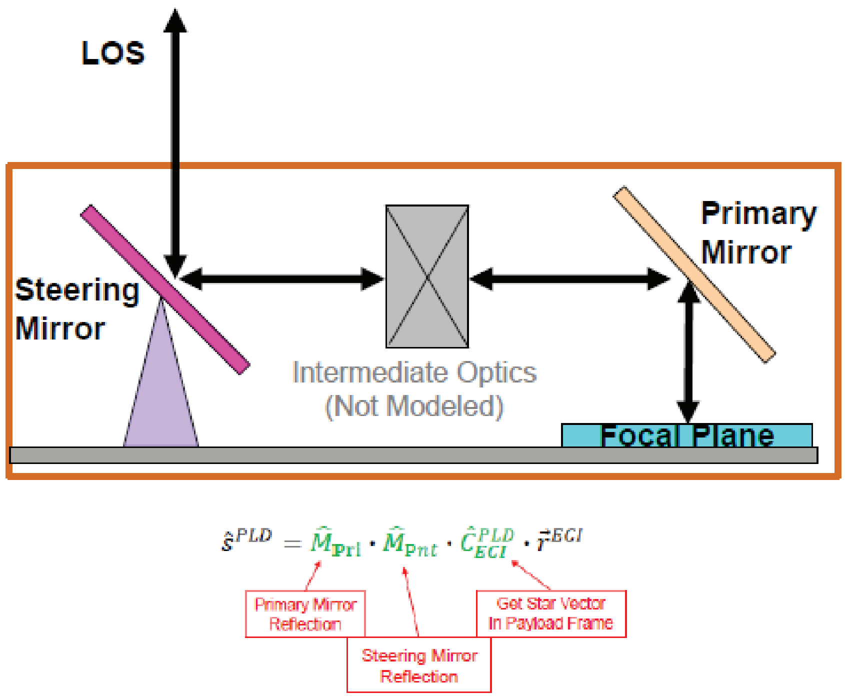

Figure 3. LOS Optical Path with Primary and Steering Mirrors

7.4 Payload Command Profiles

In this benchmark problem, the space observatory is to be subject to two typical and commonly used payload command input profiles: a linear scan and a step-stare profile, both of which are shown in Figure 4. The final jitter analysis result is the total LOS error signal under these payload commands.

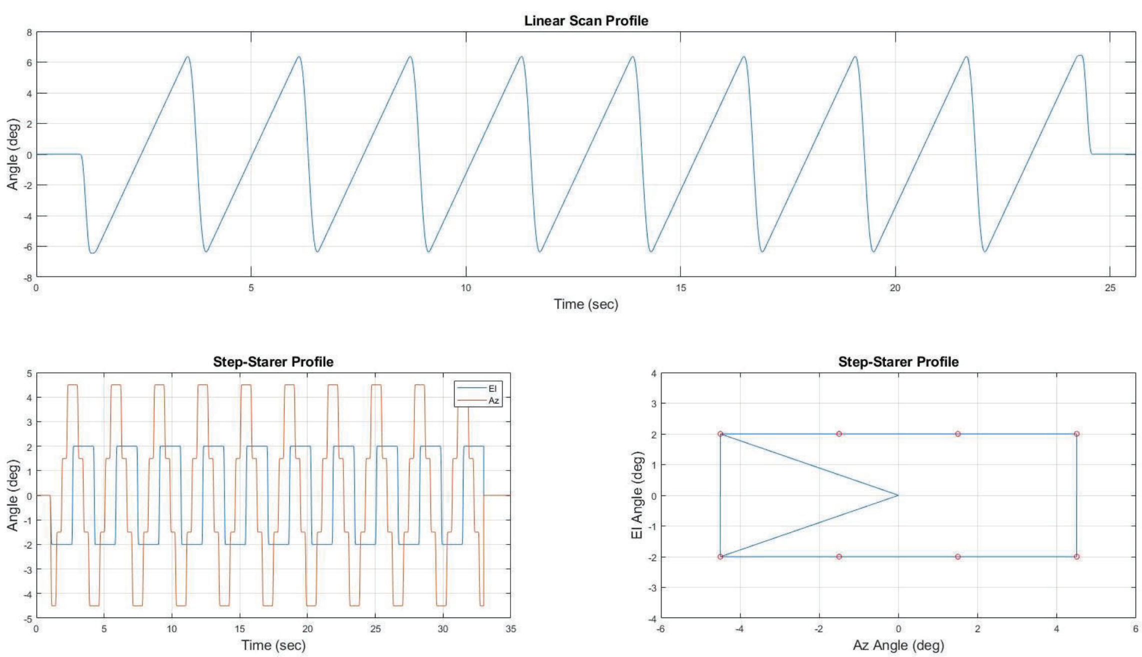

Figure 4. Payload Command Profiles (Linear and Step-Stare)

7.5 External/Internal Disturbance Model

The benchmark problem will include two primary disturbance models: one is external to the payload and the other is internal to the payload. The final jitter analysis will be performed not only in the presence of the command input profiles defined in Figure 4 but also in the presence of these payload pointing disturbances.

The first is a speed-dependent reaction wheel model of the bus attitude control actuators. This will encapsulate the physics associated with wheel static and dynamic imbalance. Obtaining reaction wheel disturbance information from industry that can be publicly shared is a challenge. The NESC assessment team, in developing the benchmark problem, opted to rely on reaction wheel disturbance modeling research performed at the Massachusetts Institute of Technology (MIT). The RWA disturbance model for this benchmark problem was built based on an Ithaco B wheel described in reference 10 and is a static-dynamic model with various tones defined in a simple sinusoidal model. This tonal model reflects only the worst-case, steady-state wheel disturbance torque at a particular speed (i.e., 3000 rpm). Figure 5 depicts the reaction wheel disturbance profile used in this benchmark problem, showing a sample power spectral density (PSD) and amplitude spectral density (ASD) of the wheel disturbances.

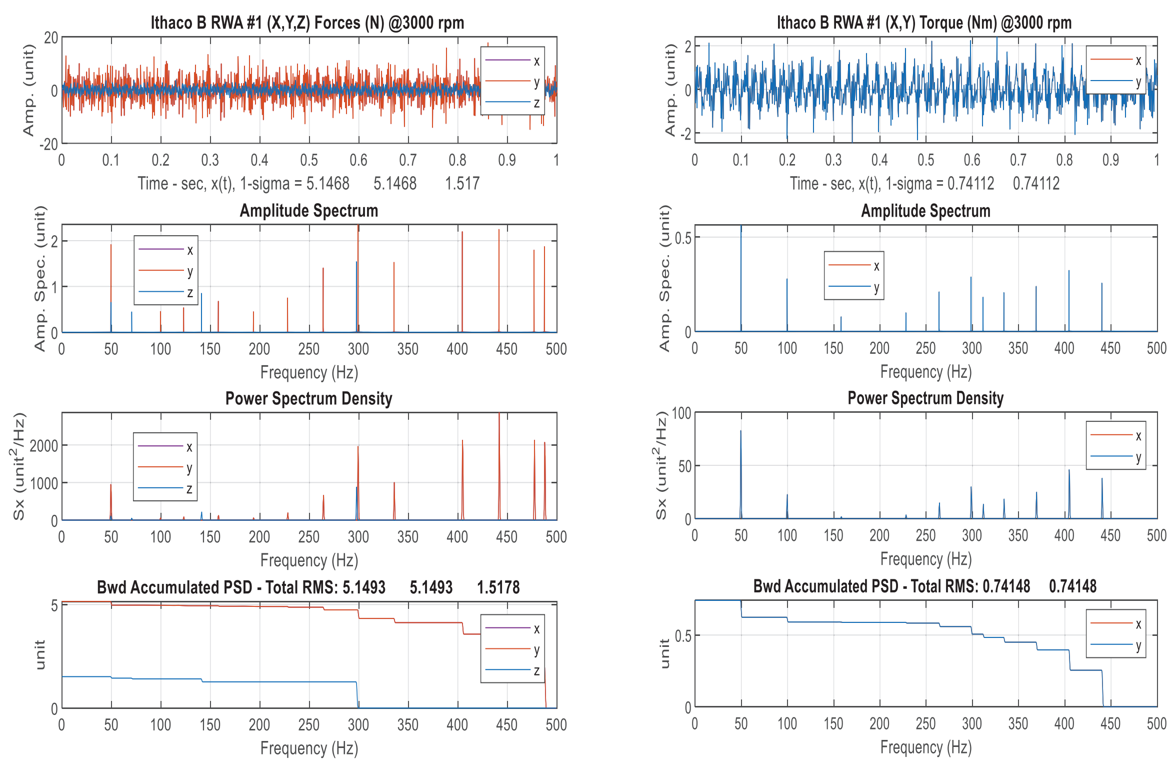

Figure 5. Reaction Wheel Disturbance Profile

The second disturbance model (Figure 6) emulates the cryocooler on the payload, often required to maintain the strict thermal requirements for a space telescope optical system. This payload's internal disturbances are typically tonal in nature. For this effort, a generic set of tones and amplitudes is constructed to act as the cryocooler disturbance, as described in reference 11. The model is simply a summation of various sinusoidal tones, $\sum A\, sin(\omega t + \phi)$, similar to the way the reaction wheel disturbance is modeled.

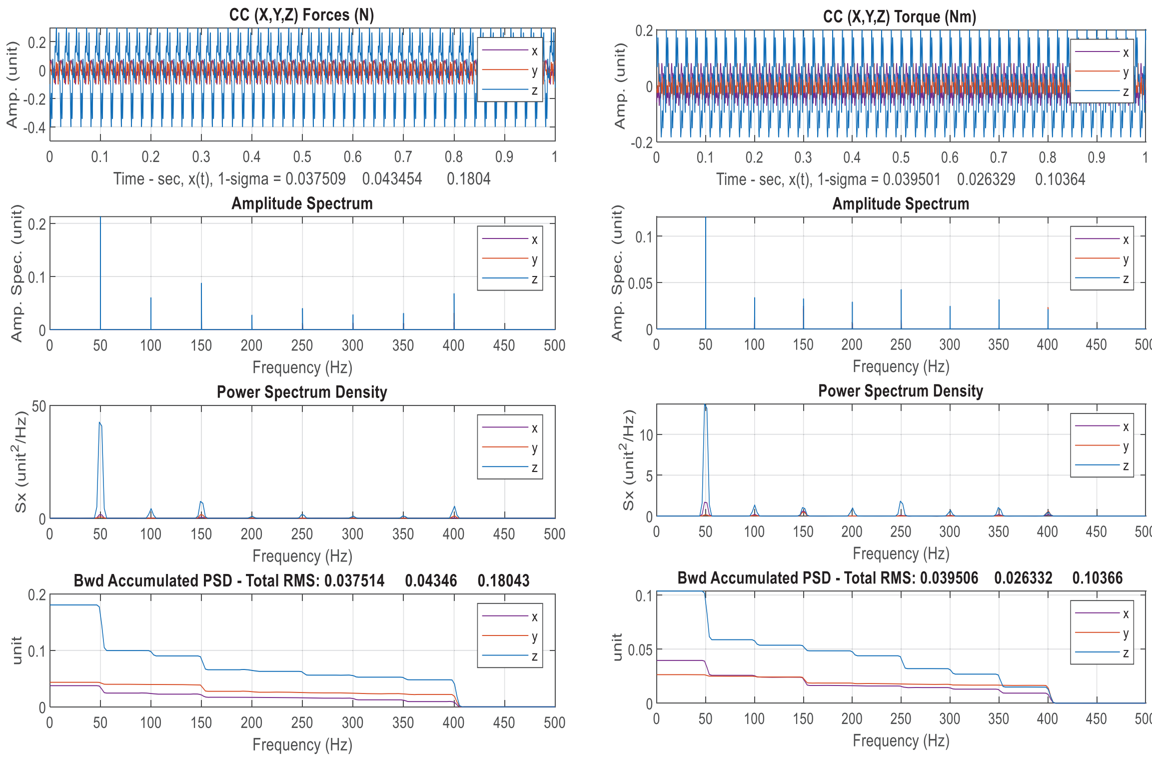

Figure 6. Cryocooler Disturbance Profile

7.6 Benchmark Problem Requirements

The final payload and bus controller design shall meet the requirements given in Table 2.

All requirements set in LOS "disturbance rejection" shown in Table 2 must be met under the slew profiles (i.e., the Linear Scanner and the Step-Stare commands) defined in Section 7.4 and the RWA/cryocooler disturbances defined in Section 7.5.

The user should define the control system design methodology to create a design satisfying the above requirements while keeping the design within the robustness boundaries shown in Figure 7 and defined by the block diagrams in Figures 8 and 9.

Table 2. Bus and Payload Requirements

Number	Requirement	Value
1: Payload/Bus Controller Design Requirements		
1-1	Stability Margins (Bus and Payload): MIMO multi-loop margins[5]	
	Gain Margin	6 dB
	Phase Margin	30° deg
1-2	Payload Control Robustness Boundaries	As described in Figure 7
1-3	Control System Bandwidth	
	Bus:	0.01 Hz, sampled at 10 Hz
	Payload:	200 Hz, sampled at 20 KHz
1-4	Payload LOS Azimuth/Elevation (Az/El) controller error (command minus feedback measurement)	< 1 μrad (zero-to-peak)
2: Line-of-Sight Disturbance Rejection		
2-1	LOS-Az/El MIMO disturbance reduction ratio	> 200:1 (Goal: 500:1)
2-2	LOS-Az/El Jitter Metric†	With 20 millisecond (msec) peak transient stay-out zone
	Step-Starer with window sizes of 20, 100, and 200 msec	
	Smear	< 0.5 μrad
	Jitter	< 0.5 μrad
	Scanner with window sizes of 20, 50, and 100 msec	
	Displacement	< 0.5 μrad
	Smear	< 0.5 μrad
†Note: The jitter metrics use Dr. Mark Pittelkau's standard definitions [ref. 14]		

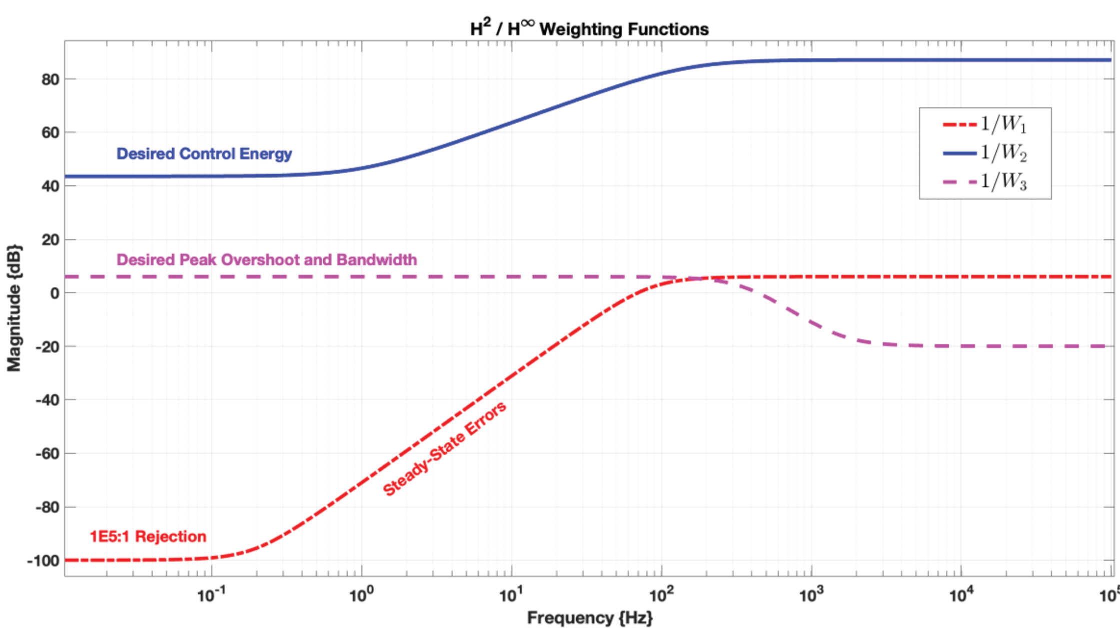

Figure 7. Robustness Boundary Requirements

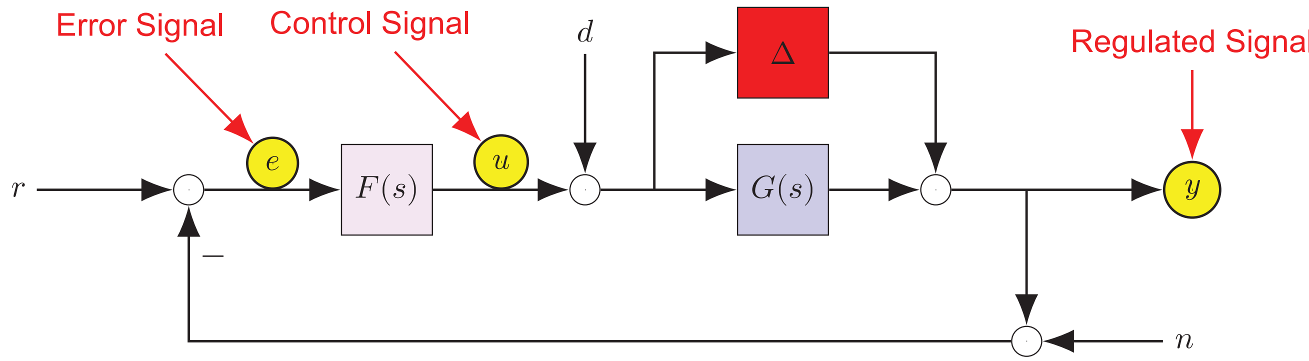

Figure 8. Control System Block Diagram in Standard Form

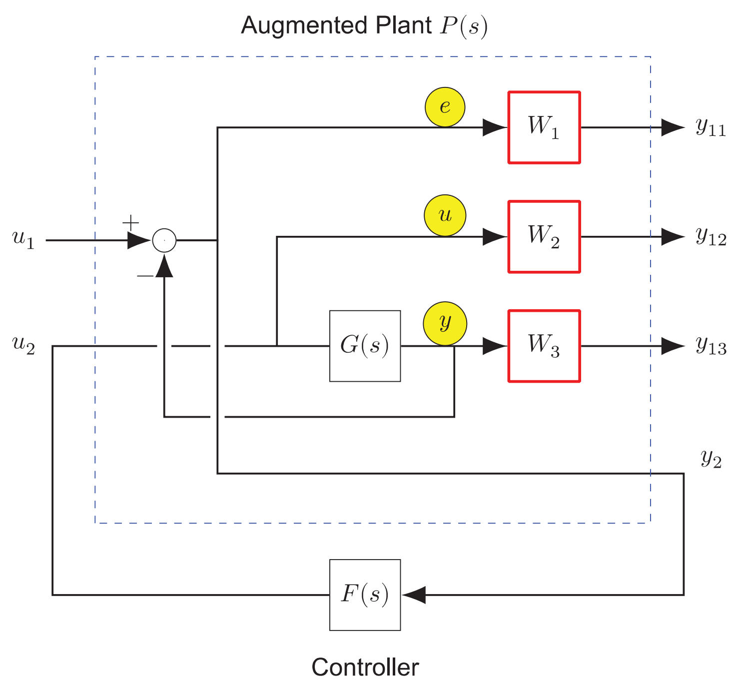

Figure 9. Augmented Control System Block Diagram Showing Weighting Functions for Establishing Robustness Boundaries

The generic weighting functions shown in Figure 9 are used to establish several robustness boundaries, as previously depicted in Figure 7. The user can choose these weighting functions using any design method for their evaluation of system performance. The user is urged to take

[5] To be informative and useful, the stability margins for a multivariable feedback system must be able to characterize the ability of the system to tolerate simultaneous gain and phase variations in all its loops. Hence, the specification in Table 2 of MIMO multi-loop stability margins. Refer to N. Lehtomaki, N. Sandell, and M. Athans, "Robustness results in linear-quadratic Gaussian based multivariable control designs," in IEEE Transactions on Automatic Control, vol. 26, no. 1, pp. 75-93, February 1981, https://ntrs.nasa.gov/citations/19810047351. This commonly cited paper provides a characterization of the robustness of a multivariable feedback system in terms of the minimum singular value of its return difference transfer function matrix. Multivariable gain and phase margins are then derived in terms of the minimum singular value.

advantage of existing standard weighting procedures in robust control [ref. 13]. For reference, the actual weighting transfer functions are provided in the user guide [ref. 15].

The weighting function $1/W_1$ (i.e., the blue curve labeled "Steady State Errors" in Figure 7) is a bound on the closed-loop sensitivity. It defines the payload system sensitivity function at the error signal, which also defines the low-frequency disturbance rejection capability. The high-frequency value of $1/W_1$ is an upper bound on sensitivity. This implies a lower bound on the magnitude of the denominator of the closed-loop transfer function, $|1+G(s)F(s)|$, which is equivalent to a disk margin, for each frequency, in the Nyquist plane. The direct current value of $1/W_1$ gives the steady-state tracking requirement. The –3-dB value of $1/W_1$ is a bandwidth constraint on the sensitivity.

The weighting function $1/W_2$ (i.e., the yellow curve labeled "Desired Control Energy" in Figure 7) is a bound on the RWA actuator torque control sensitivity in the presence of payload slewing commands and internal/external disturbance rejection.

The weighting function $1/W_3$ defines the overall payload control loop bandwidth and the high frequency unmodeled uncertain flexible dynamics boundary. This essentially bounds the output.

Jitter-specific definitions are based on those provided in reference 14. Once they are formally approved for public release, the related jitter analysis toolbox may be provided by the NESC GNC TDT upon request.

7.7 Benchmark Problem Rollout Plan

The GNC TDT is planning to roll out this benchmark problem to the community of practice in the near future**.** The benchmark problem software must first be submitted to the NASA Software Release System (SRS) to obtain formal approval for its public release. The rollout plan for releasing this benchmark problem is envisioned to initially start internally within NASA and then subsequently, once formal approval has been obtained for public release, with sharing the problem with NASA's academic and industry partners.

The fundamental plan is to leverage GNC-related conferences and similar venues to socialize the benchmark problem within the community. The intention is to leverage the existing NESC GNC TDT member relationships with the following professional organizations: the American Institute of Aeronautics and Astronautics (AIAA), the American Astronautical Society (AAS), the Institute of Electrical and Electronics Engineers (IEEE), and the International Astronautical Federation (IAF)[6]. To some extent, the process of informing the GNC community of practice about the benchmark problem has already begun at a high overview level, by virtue of technical presentations in 2023 at the Annual AAS GNC Conference [ref. 20] and at the European Space Agency (ESA) International GNC Conference [ref. 21], as depicted in Figure 10.

In addition, the team intends to exploit the Inter-Agency GNC V&V Seminar Series, with its audience of approximately 400 GNC engineers and scientists, as a forum to obtain wide visibility internationally for the benchmark problem. The team envisions holding special tutorial sessions at GNC conferences with the purpose of describing and demonstrating the benchmark problem to potential users. The NESC assessment team envisions that special sessions at GNC conferences

[6] Specifically, the IAF's Astrodynamics Committee.

could serve as forums for showcasing some of the most noteworthy user solutions highlighting innovative control designs and associated verification methods.

Figure 10. Dr. Richard Chiang and Neil Dennehy briefing ESA International GNC Conference (June 2023) Attendees at a Special Session on the Space Observatory Precision Pointing Benchmark Problem

In the spirit of understanding and learning from past benchmark problem challenges, the team will examine and consider the lessons learned and best practices from other recent benchmark problem competitions. References 16, 17, 18, and 19 describe how user-developed solutions to three different technical benchmark challenge problems were solicited, tested, compared, and evaluated. In the case of reference 17, the user solutions were part of an international benchmark problem competition. These references also discuss the ways in which users were registered for the respective challenge competitions and the means by which the benchmark problem models (software files) were shared with the registered users. The NASA Langley Research Center's 2019 challenge problem on optimization under uncertainty [Ref. 19] appears to be an excellent model to emulate for its rollout of the space observatory precision pointing benchmark problem.

On one last related note, The Aerospace Corporation raised the possibility of performing some level of verification testing of the most innovative control algorithms developed by users. The logistical details would need to be negotiated, but there is a potential for verification testing and performance evaluation using The Aerospace Corporation's pointing system HITL Fast Steering Mirror Lab Experiment Testbed facility in El Segundo, California (see Figure 11). The opportunity to have their particular LOS pointing solution hosted on the Aerospace HITL testbed would conceivably be a strong motivation for some users. This potential follow-on work is outside the scope of this assessment.

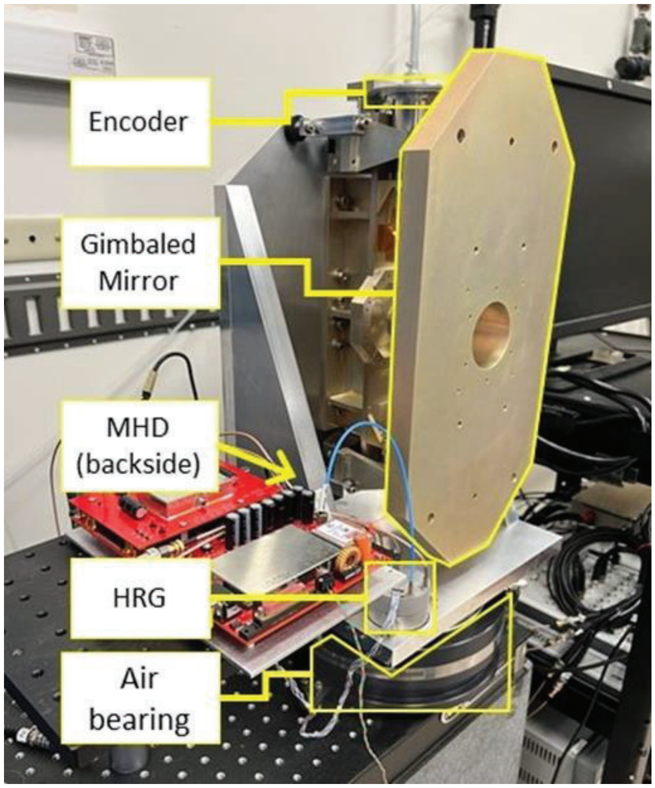

Figure 11. Fast-Steering Mirror Lab Experiment HITL Testbed (The Aerospace Corporation, El Segundo, CA)

8.0 Conclusions

The conclusions from this precision pointing benchmark problem assessment are:

C-1. This report documents the space observatory precision pointing benchmark problem development, including:

- A space observatory model consisting of a bus and steerable optical payload
- Uncertainties including variable mass properties and variable flexible-body dynamics variations
- Adaptations for degraded sensors and actuators
- Capability to use the NESC pointing error metrics toolbox to generate and evaluate performance using standard metrics

C-2. The benchmark problem will allow users to develop innovative bus and payload control algorithms and assess their performance in the following critical areas:

- Controller stability margins and robustness requirements
- Satisfying stringent jitter requirements while demonstrating aggressive attitude agility
- Concept of operations for payload observations

C-3. The user guide describes the benchmark problem software functionality, inputs, and outputs.

C-4. The MathWorks MATLAB® files representing the benchmark problem will be submitted through the NASA Software Release System (SRS) for approval prior to public release.

C-5. The NESC GNC TDT is planning to roll out this benchmark problem to the community of practice in the near future. The benchmark problem software must be submitted to the NASA Software Release System (SRS) to obtain formal approval for public release. This rollout plan for releasing this benchmark problem is envisioned to initially start internally within NASA and then subsequently, once formal approval has been obtained for public release, with sharing the problem with NASA's academic and industry partners. The fundamental plan is to leverage GNC-related conferences and similar venues to socialize the benchmark problem within the community of practice.

8.1 Concluding Remarks

In summary, a new benchmark problem for the precision pointing of a space observatory (e.g., a space telescope) has been formulated. The NESC assessment team has worked to ensure the problem is sufficiently realistic, representative, and challenging to inspire government, academic, and industry researchers to create innovative, and perhaps non-traditional and/or alternative, design solutions. The assessment team believes this benchmark problem is conducive to the types of control strategies that users can potentially apply. Classical LTI controllers, which are relatively easy to verify, are expected as potential user solutions, but it is unlikely that LTI controllers can meet all the benchmark requirements.

It is anticipated that this new benchmark problem will provide a common framework for researchers to explore and investigate various advanced control techniques that the aerospace industrial community has been hesitant to employ due to a perception of higher risk and/or unfamiliarity. While academic researchers are familiar with advanced control techniques, unfortunately many do not have access to recognized high-fidelity benchmark problems. This benchmark problem can serve as a bridge between the academic and industrial communities.

It is believed that going forward this benchmark problem could have significant influence on the field by providing an opportunity for users to experiment with solutions based on neural networks, H^{∞}, adaptive methods, machine learning, model predictive control, on-line convex optimization, and other modern, novel, and evolving techniques. These techniques have been studied by researchers but have not traditionally been applied to NASA's operational spacecraft. It must be considered that these advanced techniques, while offering the promise of improved performance, pose fundamental stability and robustness verification challenges that must be addressed. Thus, a critical and necessary part of a complete and comprehensive user response to this new benchmark problem will be the demonstration of an appropriate and satisfactory methodology for the verification of the proposed design solution's stability and robustness properties.

9.0 Alternate Technical Opinion(s)

No alternate technical opinions were identified during the course of this assessment by the NESC assessment team.

10.0 Other Deliverables

In addition to this final report, this assessment included the following deliverables:

1. A conference paper and presentation 2023 American Astronautical Society (AAS) GNC Conference in Breckenridge, Colorado in February 2023 [ref. 20]

2. A conference presentation at the European Space Agency International GNC Conference in Sopot, Poland, in June 2023 [ref. 21]
3. Space Observatory Precision Pointing Benchmark Problem Software (MATLAB® files)
4. User Guide for the Precision Pointing Benchmark Problem [ref. 15]

The two technical presentations cited above were published to provide visibility into and to communicate the creation of the new Gen II space observatory precision pointing benchmark problem to the GNC community.

11.0 Recommendations for the NASA Lessons Learned Database

No recommendations for NASA standards, specifications, or procedures were identified as a result of this assessment.

12.0 Recommendations for NASA Standards, Specifications, Handbooks, and Procedures

No recommendations for NASA standards, specifications, or procedures were identified as a result of this assessment.

13.0 Acronyms and Nomenclature List

μrad	Microradian
AAS	Advanced Avionics System
AIAA	American Institute of Aeronautics and Astronautics
ASD	Amplitude spectral density
Az	Azimuth
BW	Bandwidth
CSI	Control-structure interaction
ECI	Earth-Centered Inertial
El	Elevation
FSM	Fast-steering mirror
Gen I	Generation I
Gen II	Generation II
GNC	Guidance, navigation, and control
HITL	Hardware-in-the-loop
IEEE	Institute of Electrical and Electronics Engineers
LOS	Line of sight
LVDT	Linear variable differential transformer
msec	Millisecond
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
ODR	Optical Disturbance Rejection
PSD	Power spectral density
PZT	Piezoelectric transducer
RWA	Reaction wheel assembly
SA	Solar array

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14. ABSTRACT
An interagency workshop in May 2021 on guidance, navigation, and control (GNC) verification and validation (V&V) methods and techniques identified needs for the formulation and public release of relevant V&V benchmark problems as a practical way forward for the discipline. A decision was made by the NASA Technical Fellow for GNC and the NASA Engineering and Safety Center (NESC) GNC Technical Discipline Team (TDT) to produce a benchmark problem focusing on the problem of space observatory precision pointing. This report contains the results of the NESC assessment.

15. SUBJECT TERMS
NASA Engineering and Safety Center; Guidance, Navigation, and Control; Verification and Validation; Control-Structure Interaction; Line-of-Sight

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