

Spacecraft Observatory Benchmark Problem for Optical Disturbance Rejection

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Abstract

Since mid-1980s NASA has launched several first-generation interplanetary observatory missions. A salient feature of these missions has been the mounting of the optical payload on top of a large flexible space structure. This imposes challenging control-structure interaction problems (CSI) that have been studied over several decades. The Dec. 2021 launch of the James Webb Telescope marks the latest example of such a mission. One way to encourage development of novel control methods is to provide a benchmark problem for researchers. By the mid-2000s, there were a few well-known benchmark problems developed by the control community with a focus on CSI applications. However, in the past 15 years, the control challenges in optical observation missions have shifted from CSI to line-of-sight (LOS) precision pointing. This is because popular designs of the second-generation (Gen II) space earth missions have eliminated the large structure interface by mounting the optical payload directly on top of a rigid bus platform. The focus now is to achieve accurate pointing with maximum rejection of the surrounding disturbances. The NASA Safety and Engineering Center (NESC) has tasked The Aerospace Corporation to develop a Benchmark Problem to study the challenging control issues that Gen II observatory missions encounter. This software tool is to be released as a public domain platform aimed at government, academic, and industry researchers. The focus of this benchmark problem is for researchers to design a set of innovative payload control laws with the maximum Optical Disturbance Rejection (ODR) capability to meet a set of pre-defined μ rad-level of LOS jitter requirements. This paper describes the development of the benchmark problem. Aerospace/NASA will provide an integrated LOS plant model and disturbance/command profiles for users to run their design and simulation with as well as a user's guide describing the required interfaces. The Aerospace Corp is also working to develop a hardware fast steering mirror testbed for users to demonstrate their innovative design in real hardware, if so desired.

I. Introduction

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 its industry partners. 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 several aspects involved are: large-space-structure driven dynamics and control, precision optical payload pointing, pointing performance metrics, payload dynamics modeling, disturbance rejection, 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 co-located control law design.

Several engineering benchmark problems have been developed since the late 1980s and have been shown to be a useful means to study various ways to solve a common, standardized reference problem [1,2,3,4,5,6,7]. We refer those applications as Gen I Control Structure Interaction (CSI) problem. The purpose of this paper is to introduce a developed common Next Generation (or Gen II) (i.e., technically consistent) space observatory benchmark problem established and easily accessible that will provide the guidance, navigation, and control (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 observatory spacecraft will be the perfect platform for the GN&C academic and industry communities to provide their innovative optical disturbance rejection (ODR) solution and LOS pointing capability to demonstrate what's achievable in this most challenging and essential of space missions. Figure 1 illustrates the control loop closures in Gen I vs. Gen II.

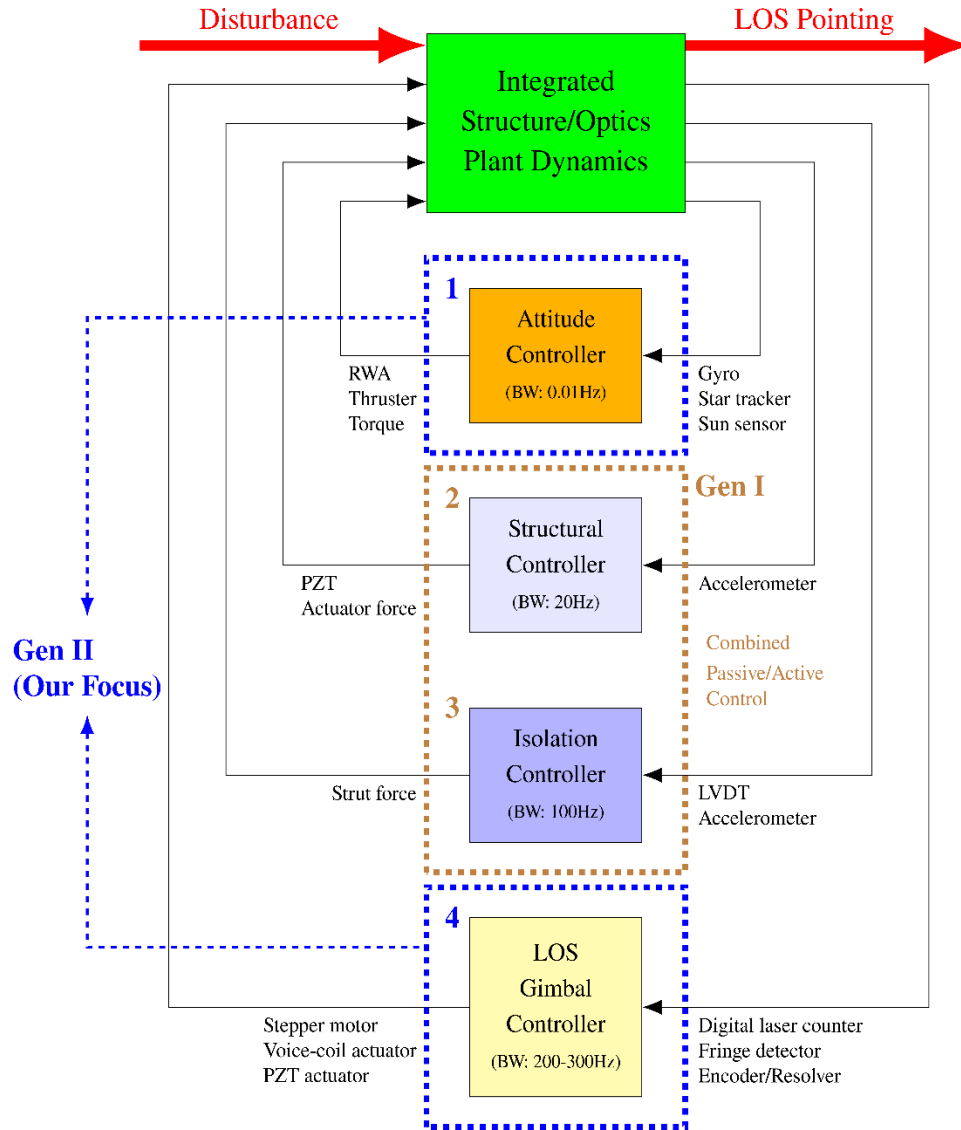


Figure. 1 Multi-Layer Active Optical/Structure Control System.

Gen I CSI problems have been focusing on building layers 2 & 3 to suppress the structure vibrations. Gen II ODR problems that NASA/Aerospace proposed here will focus on the development of Layer 4 to maximize the optical payload disturbance rejection capability.

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

Table 1 Control Design Approaches Gen I vs. Gen 2

Gen I - Well Established CSI Problem

Benchmark Problem		Layer 1 (BUS Control)	Layer 2 (Structure Control)	Layer 3 (Isolation Control)	Layer 4 (LOS Control)	Notes
Gen I (CSI)	1 Jose (1985-1988)		Collocated Rate Feedback		H-infinity	* Large space structure * Study of structure/LOS control
	2 CSI Phase A (1991-1993)		Non-Collocated H-infinity			* Large space structure * Study of structure control
	3 CSI Phase B (1993-1996)		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)		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)		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

II. Gen II Benchmark Problem

The principal objective of the benchmark problem design is to build the community's expertise in robust LOS control algorithms for optical payloads. The user will only be able to drive the payload's optical LOS vector by controlling a fast-steering mirror (FSM) which uses FSM encoder, payload gyro, and payload star tracker measurements. The LOS vector will need to be stabilized during optical sensor integration windows to meet jitter, smear, and displacement requirements in the presence of 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. Actual jitter, smear, and displacement requirements will be defined in such a way that they cannot be met without the use of an active disturbance rejection scheme.

The following subsections will discuss 1) spacecraft model; 2) mapping from gimbal to LOS in ECI frame; 3) the command profiles and 4) the external/internal payload disturbances. These important benchmark problem data will be provided to the users in either ASCII or binary format as user desired. No specific design/simulation tools or platform is required to do the design and/or analysis.

1). Plant Model – Observatory Spacecraft

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 MATLAB code to construct a continuous state space model for stability analysis and LOS jitter analysis.

The bus is one rigid body. There are grid points for reaction wheel disturbance force and torque inputs, reaction wheel spin axis torque inputs, bus angle outputs (i.e., star tracker attitude), and bus gyro rate outputs.

Each solar array (SA) consists of 4 rigid panels with one torsional spring between each panel (along the panel edge), and 3 torsional springs connecting the first panel to the bus. Springs are tuned to give the first fixed base SA bending mode at approximately 1.0 Hz, and SA torsional mode at approximately 1.5 Hz.

The payload consists of a rigid optical bench (with rigidly connected focal plane and primary mirror) and a rigid steering mirror with 2 gimbal axis DOF between it and the bench. There is a 2.0 Hz flexure spring about each gimbal axis. The payload is connected to the bus with 3 translational and 3 torsional springs. Springs are tuned to give payload rotational modes at approximately 50-80 Hz, and translational modes at approximately 30-60 Hz. There are grid points for gimbal torque inputs, cryocooler disturbance torque inputs, gimbal angle outputs, and payload gyro rate outputs.

The system model also includes a LOS error output (X/Y-angles, with nominal LOS along Z-axis when gimbal angles are zero) based on commanded vs. truth bus attitude, commanded vs. truth gimbal angles, and flex motion (i.e., payload angles relative to bus).

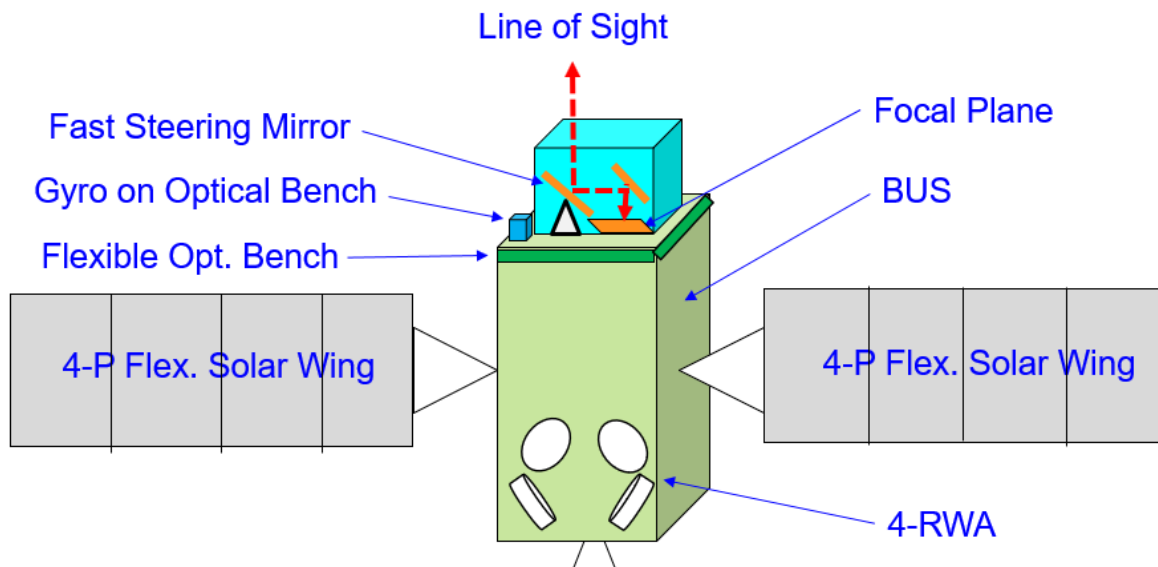


Figure 2 Observatory Spacecraft.

All input/output channel descriptions will be well defined in detailed in the User Guide.

2). Focal Plane Vector Mapping to LOS in ECI Frame

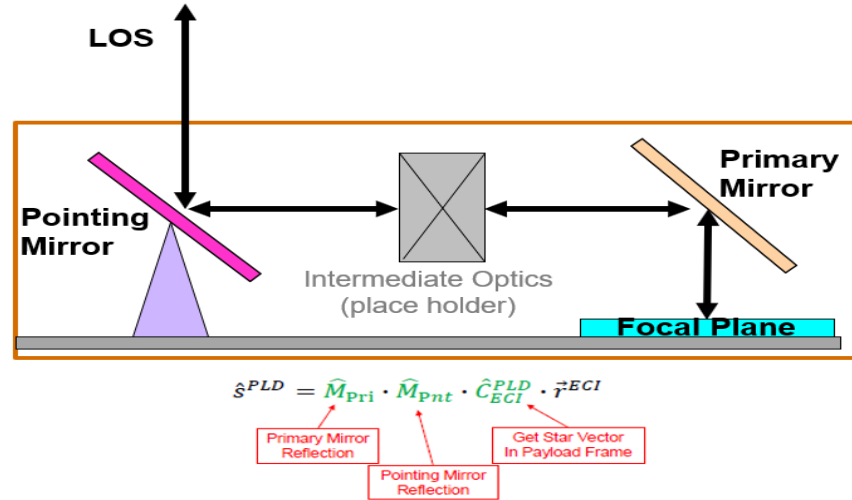


Figure 3 LOS Optical Path with Primary and Pointing Mirrors.

The LOS optical path is modeled with two mirrors. The LOS in free space reflects off a gimbaled Steering Mirror, passes through intermediate optics (not modeled here), reflects off a fixed Primary Mirror, and hits the focal plane. The LOS is affected by 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 because they don't affect the basic ODR benchmark problem design, instead they may increase the simulation complexity and result long execution time for design iterations.

3). Payload Command Profiles

The spacecraft is to be subject to two typical payload command profiles: a linear scan, and a step-stare profile, as shown in Figure 4. The final jitter analysis result will be the total error signals under these payload commands.

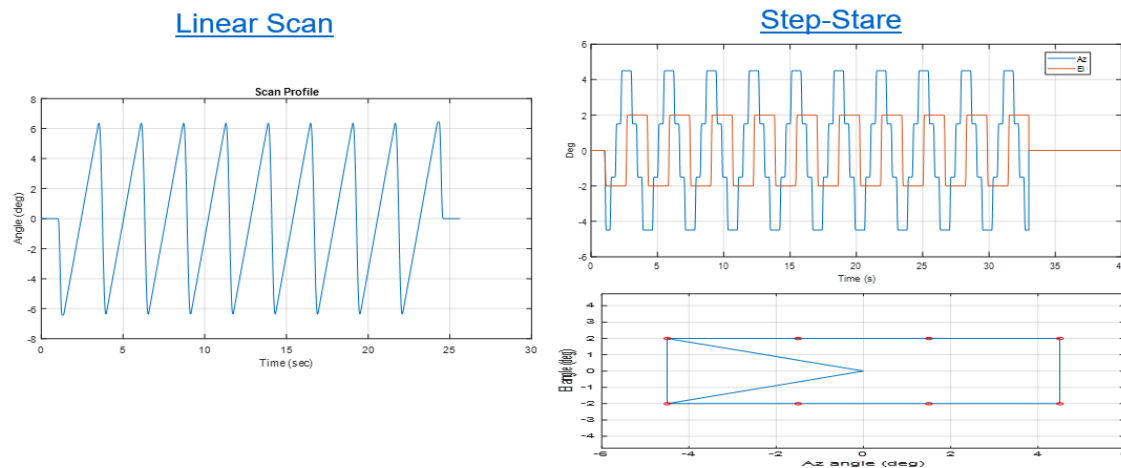


Figure 4. Payload Command Profiles.

4). External/Internal Disturbance Model

The benchmark problem will include two primary disturbance models – one is external of the payload, the other is internal to the payload.

The first is a speed-dependent reaction wheel model of the spacecraft bus actuators. This will encapsulate physics associated with wheel imbalance. The flexible reaction wheel mount can also incur additional disturbances; this flexibility will lead to structural modes within the reaction wheel assembly which can couple with the reaction wheel motion to generate a varied disturbance profile at different speeds.

Figure 5 shows a sample of PSD and ASD of the wheel disturbances 3000 rpm. The model was built based on Itacho B wheel described in [Ref. 8]. It's 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 (3000 rpm in benchmark problem).

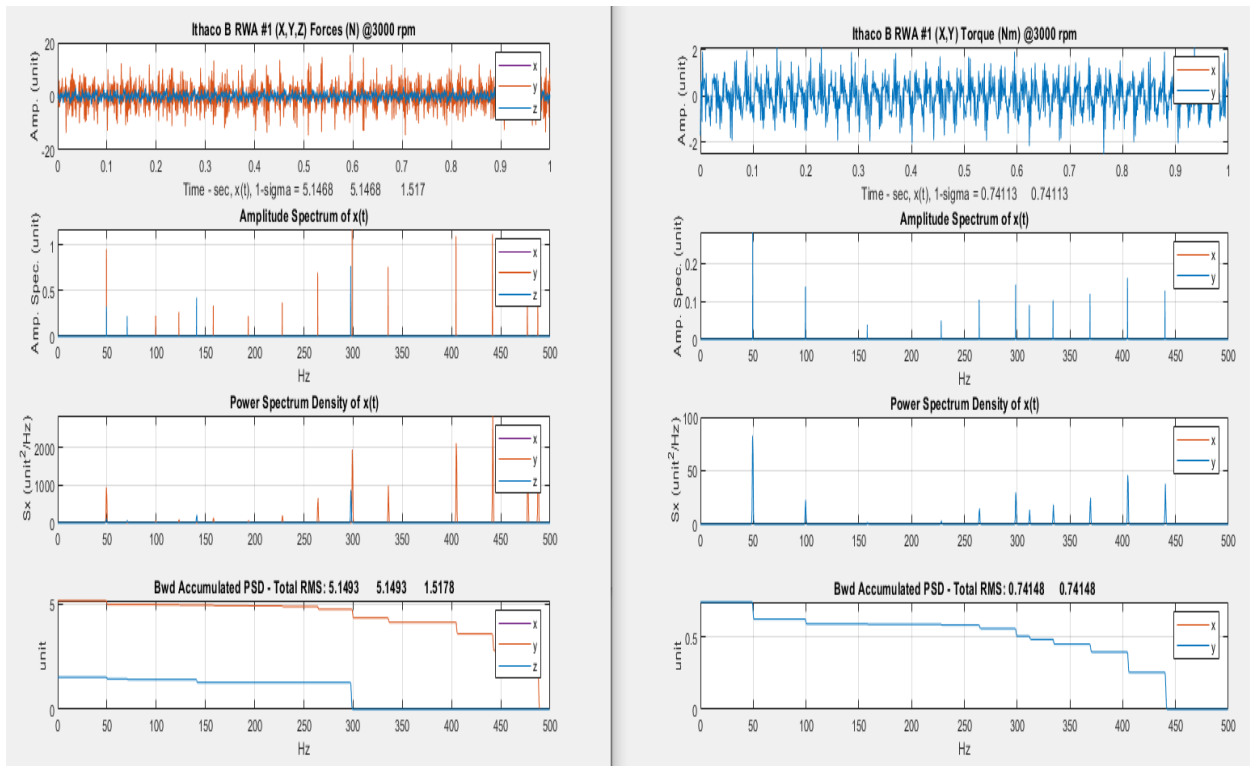


Figure 5 External RWA Disturbance Profile.

The second disturbance model will emulate the cryocooler on the payload, often required to maintain the strict thermal requirements for an optical system. This payload's internal disturbances are typically tonal in nature; for this effort, we will construct a generic set of tones and amplitudes to act as the cryocooler disturbance, following the model in [9].

The model itself is simply a summation of various sinusoidal tones $\sum A \sin(\omega t + \phi)$ just like RWA.

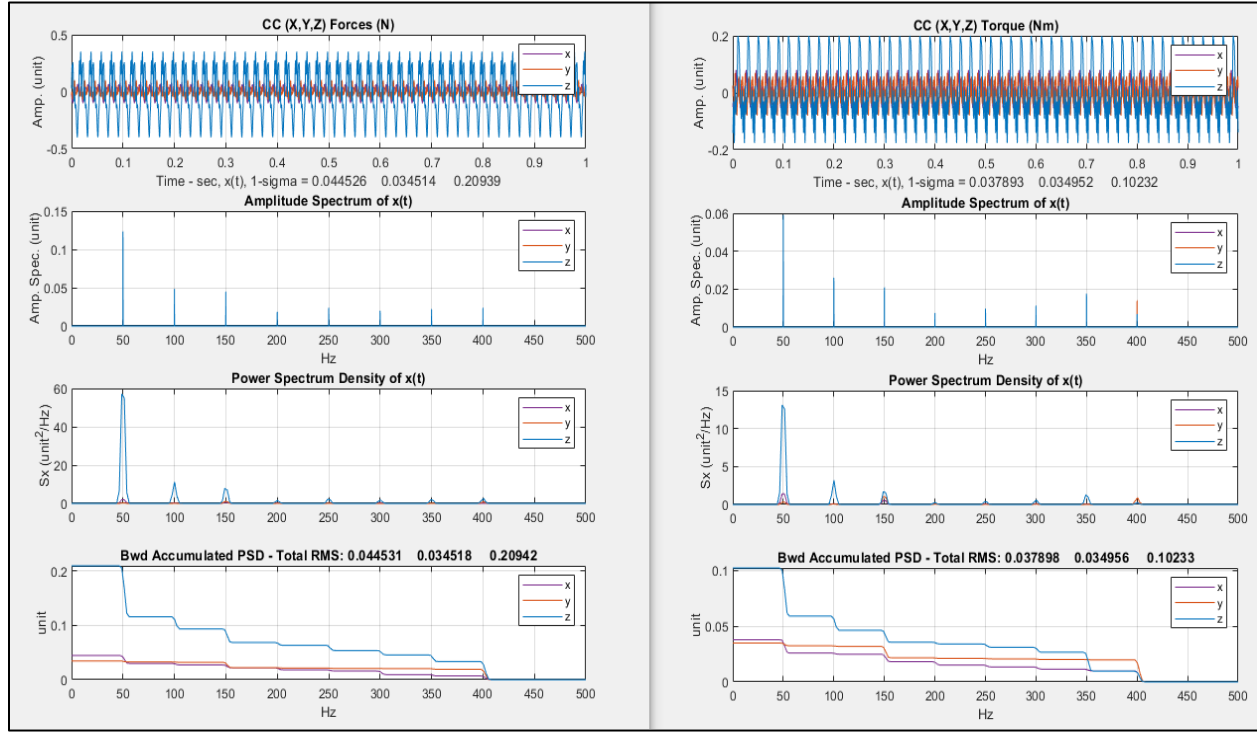


Figure 6 Internal Cryocooler Disturbance Profile.

III. Benchmark Problem Requirements

The final payload and BUS controller design shall meet the following requirements.

[AN001] Control design (Payload/BUS Controller)

- [AN001-1] Stability Margins (BUS and Payload): MIMO (multi-input-multi-output) [6dB, 30deg] [10]
- [AN001-2] Payload Control Robustness Boundaries (see Figure 8)
- [AN001-3] Control System BW: BUS – 0.01 Hz (Sampled at 10 Hz), Payload - 200 Hz (Sampled at 20 KHz)
- [AN00-4] Payload LOS Az/El controller error (command minus feedback measurement) < 1 urad (zero to peak)

[AN002] LOS Disturbance Rejection

- [AN002-1] LOS-Az/El MIMO disturbance reduction ratio: > 200:1 (Goal: 500:1) [2, 12, User Guide]
- [AN002-2] LOS-Az/El Jitter Metric (using the Pittelkau standard definitions [11] with 20 msec peak transient stay out zone)
 - Step-Starrer with Window Sizes = [20, 100, 200] msec
 - Smear < 0.5 urad
 - Jitter < 0.5 urad
 - Scanner with Window Size = [20, 50, 100] msec

- $Displacement < 1 \text{ urad}$
- $Smear < 1 \text{ urad}$

All above “disturbance rejection” requirements [AN002] need to be met under Aerospace/NASA defined slew profiles (Scanner and Step-Starer) and RWA/CC disturbances defined in Section II.

The robustness boundaries shown in Figure 8 is based on the desired frequency response in Figure 7.

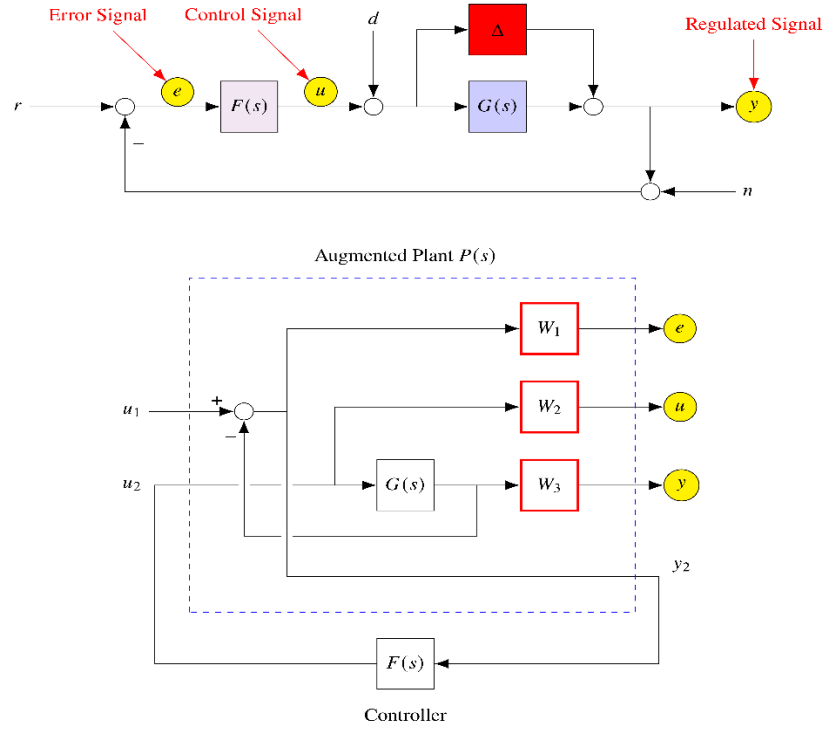


Figure 7. Robustness Boundary Definitions.

Robustness Requirements

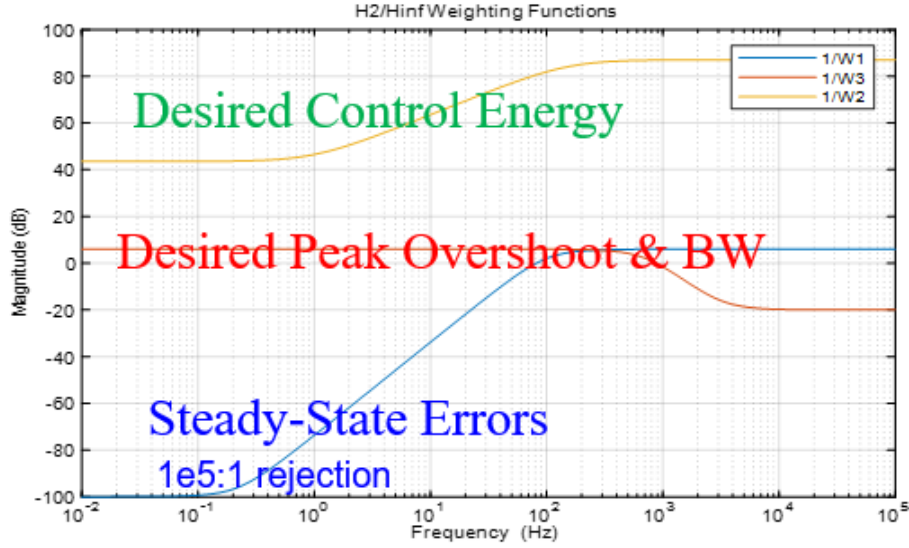


Figure 8. Robustness Boundary Requirements.

Weighting functions $1/W1$ defines the payload system sensitivity function at error signal, which also defines the low frequency range disturbance rejection capability. Weighting function $1/W2$ defines the actuator torque limits in the presence of payload slewing commands as well as internal/external disturbances. Weighting Function $1/W3$ defines the overall payload control loop BW and high frequency unmodeled uncertain flexible dynamics boundary. The actual weighting function will be provided in the User Guide [12].

The user may employ any control system design methodology to come up with a design satisfying the above requirements [AN001, AN002] while keeping the design within the above robustness boundaries.

Jitter specific definitions are based on [11]. The related jitter analysis tools may be provided upon request.

IV. Conclusion

Gen II Observatory Spacecraft benchmark problem is defined in this paper. The design objective is to come up a set of payload and BUS controllers that can meet stability, robustness, pointing performance as well as disturbance rejection, while maintaining the optical payload command following, shift, smear, and jitter within the levels defined in Section III.

The payload slewing commands are derived arbitrarily and internal/external disturbances are derived from public domain references. This benchmark problem of observatory spacecraft has been made from scratch with an Aerospace developed prototype design to study the feasibility

and on the other hand to make sure the problem is representative and challenging enough to inspire industrial and academic users to come up with their innovative design.

For programmatic and technical issues, please contact Cornelius Dennehy of the NASA Engineering and Safety Center (NESC) cornelius.j.dennehy@nasa.gov and Uday Shankar uday.shankar@jhuapl.edu of Johns Hopkins Applied Physics Lab. For questions on dynamic models, disturbance, slew commands and Design User Guide, please contact Richard Y. Chiang, richard.y.chiang@aero.org, Richard Dolphus, richard.m.dolphus@aero.org, Michael Andonian, michael.andonian@aero.org, and Wei Huang wei.huang@aero.org of Aerospace Corp.

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