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IMAGING X-RAY POLARIMETRY EXPLORER MISSION ATTITUDE DETERMINATION AND CONTROL CONCEPT

Jeff Bladt,[1] William D Deininger,[2] William Kalinowski,[3] Mary Boysen,[4] Kyle Bygott,[5] Larry Guy,[6] Christina Pentz,[7] Chris Seckar,[8] John Valdez,[9] Jeffrey Wedmore,[10] Brian Ramsey,[11] Stephen L. O'Dell,[12] and Allyn Tennant[13]

The goal of the Imaging X-Ray Polarimetry Explorer (IXPE) Mission is to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." X-ray polarimetry is the focus of the IXPE science mission. Polarimetry uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable. The IXPE Observatory consists of Spacecraft and Payload modules. The Payload includes three polarization sensitive, X-ray detector units (DU), each paired with its corresponding grazing incidence mirror module assemblies (MMA). A deployable boom provides the correct separation (focal length) between the DUs and MMAs. These Payload elements are supported by the IXPE Spacecraft. A star tracker is mounted directly with the deployed Payload to minimize alignment errors between the star tracker line of sight (LoS) and Payload LoS. Stringent pointing requirements coupled with a flexible structure and a non-collocated attitude sensor-actuator configuration requires a thorough analysis of control-structure interactions. A non-minimum phase notch filter supports robust control loop stability margins. This paper summarizes the IXPE mission science objectives and Observatory concepts, and then it describes IXPE attitude determination and control implementation. IXPE LoS pointing accuracy, control loop stability, and angular momentum management are discussed.

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[1] Principal Engineer, IXPE ADCS Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[2] Staff Consultant, IXPE Mission Systems and Payload Engineer, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[3] Principal Engineer, IXPE Spacecraft Systems Engineering and C&DH Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[4] Principal Engineer, IXPE Structural Design Engineering Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[5] Principal Engineer, IXPE Flight Software Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[6] Staff Consultant, IXPE Mechanisms Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[7] Senior Engineer, IXPE Structural Analyst, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[8] Principal Engineer, IXPE Alignment Metrology Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[9] Principal Engineer, IXPE Thermal Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[10] Senior Engineer, IXPE Mechanical Design Lead, Ball Aerospace, P.O. Box 1062 Boulder, CO 80306.
[11] IXPE Deputy Principal Investigator (DPI), IXPE Payload Lead, Research Astrophysicist, NASA Marshall Space Flight Center, Huntsville, AL 35812.
[12] IXPE Project Scientist, Research Astrophysicist, NASA Marshall Space Flight Center, Huntsville, AL 35812.
[13] IXPE Science Operations Center Lead, Research Astrophysicist, NASA Marshall Space Flight Center, Huntsville, AL 35812.

INTRODUCTION

The IXPE NASA Small Explorer (SMEX) Mission is an international collaboration led by NASA Marshall Space Flight Center (MSFC) as the Principal Investigator (PI) institution (Dr. Martin Weisskopf) and includes Ball Aerospace (Ball), University of Colorado / Laboratory for Atmospheric and Space Physics (CU/LASP), as well as the Italian Space Agency (ASI) with Istituto Nazionale di Astrofisica/Istituto di Astrofisica e Planetologia Spaziale (INAF/IAPS) and Istituto Nazionale di Fisica Nucleare (INFN) as major international partners.[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]

The goal of IXPE is to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." X-ray polarimetry is the focus of the IXPE science mission. X-ray polarimetry uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable.

The IXPE Observatory consists of Spacecraft and Payload modules. The Payload includes three polarization sensitive, X-ray detector units (DU), each paired with its corresponding grazing incidence mirror module assembly (MMA). A deployable boom provides the correct separation (focal length) between the DUs and MMAs. These Payload elements are supported by the IXPE Spacecraft.

MSFC provides the mirror module assembly (MMA) X-ray optics and Science Operations Center (SOC) along with mission management and systems engineering.[11, 12, 13, 14, 15] INAF/IAPS and INFN provide the unique polarization-sensitive detectors, detector units (DU) and detectors service unit (DSU).[3, 16, 17, 18, 19, 20, 21] Ball is responsible for the Spacecraft, Payload mechanical elements and flight metrology along with Payload, Spacecraft and System I&T followed by launch and operations. The Mission Operations Center (MOC) is located at CU/LASP.[22, 23, 24]

The IXPE Project completed its Phase A activities in July 2016 with the submission of the Concept Study Report (CSR) to the NASA Explorers Program Office. NASA considered three SMEX mission concepts for flight and selected the IXPE Project as the winner in January 2017.[25] The Project entered Phase B on February 1, 2017.

This paper summarizes the IXPE mission science objectives, the Observatory implementation, and the attitude determination and control subsystem (ADCS). Next, this paper discusses three key ADCS features: (i) control loop stability, given low frequency structural dynamic modes and non-collocated attitude sensor-actuator configuration, (ii) Observatory LoS pointing accuracy and x-ray telescope co-alignment accuracy supporting science data collection, and (iii) angular momentum management accommodating large gravity gradient torque.

SCIENCE OBJECTIVES

IXPE directly supports NASA's first strategic objective in Astrophysics: "Discover how the universe works".[26] In particular, it addresses a key science goal of NASA's Science Mission Directorate: "Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity." IXPE will expand understanding of high energy astrophysical processes, specifically the polarimetry of cosmic sources with special emphasis on objects such as neutron stars and black holes. IXPE addresses two specific science objectives by obtaining X-ray polarimetry and polarimetric imaging of cosmic sources to:

- Determine the radiation processes and detailed properties of specific cosmic X-ray sources or categories of sources

- Explore general relativistic and quantum effects in extreme environments.

NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions", also recommends such measurements.[27]

IXPE uses imaging and X-ray polarimetry to expand the X-ray observation space, which historically has been limited to imaging, spectroscopy, and timing. These advances will provide new insight as to how X-ray emission is produced in astrophysical objects, especially systems under extreme physical conditions—such as neutron stars and black holes. Polarization uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise easily measurable. Hence, IXPE complements all other investigations in high-energy astrophysics by adding the important and relatively unexplored dimensions of polarization to the parameter space for exploring cosmic X-ray sources and processes, and for using extreme astrophysical environments as laboratories for fundamental physics.

The primary science objectives of IXPE are:

- Enhance our understanding of the physical processes that produce X-rays from and near compact objects such as neutron stars and black holes.
- Explore the physics of the effects of gravity, energy, electric and magnetic fields at their extreme limits.

OBSERVATORY IMPLEMENTATION

IXPE is designed as a 2-year mission with launch in April 2021. IXPE launches to a circular low Earth orbit (LEO) at an altitude of 540 km and an inclination of 0 degrees. The Payload uses a single science operational mode for capturing the X-ray data from science targets. The mission design follows a simple observing paradigm: pointed viewing of known X-ray sources (with known locations in the sky) over multiple orbits (not necessarily consecutive orbits) until the observation is complete. This means that the attitude determination and control subsystem design enables the IXPE Observatory to remain pointed at the same science target for days at a time.

The Observatory is designed to support IXPE measurement requirements. Key design drivers include pointing stability in the presence of various disturbances, particularly gravity gradient torques, and minimization of South Atlantic Anomaly (SAA) passes which makes the zero-degree inclination orbit the best available choice. A nominal IXPE target list is known in advance with targets distributed over the sky. The Observatory has observational access to an annulus normal to the Sun line at any given time with a width ±30° from Sun-normal. This orientation allows the Observatory to collect all necessary science data during the mission while keeping the solar arrays oriented toward the sun and maintaining sufficient power margins. Typically, each science target is visible over an approximate 60-day window and can be observed continuously for a minimum time of 56.7 minutes each orbit. The IXPE Observatory communicates with the ASI-contributed Malindi ground station via low-gain S-band link. As such, large angle slew and settle activity is kept to a minimum.

As noted in the literature, the IXPE Spacecraft is based on Ball's BCP-100 small spacecraft product line.[28] Figure 1 illustrates the IXPE Observatory with DUs mounted to the Spacecraft top deck and MMAs integrated into the mirror module support structure (MMSS) at the opposite end of the deployable, coilable boom.[29] A pair of star tracker optical heads (OH) are mounted on opposite ends of the Observatory, anti-boresighted from one another to prevent simultaneous Earth

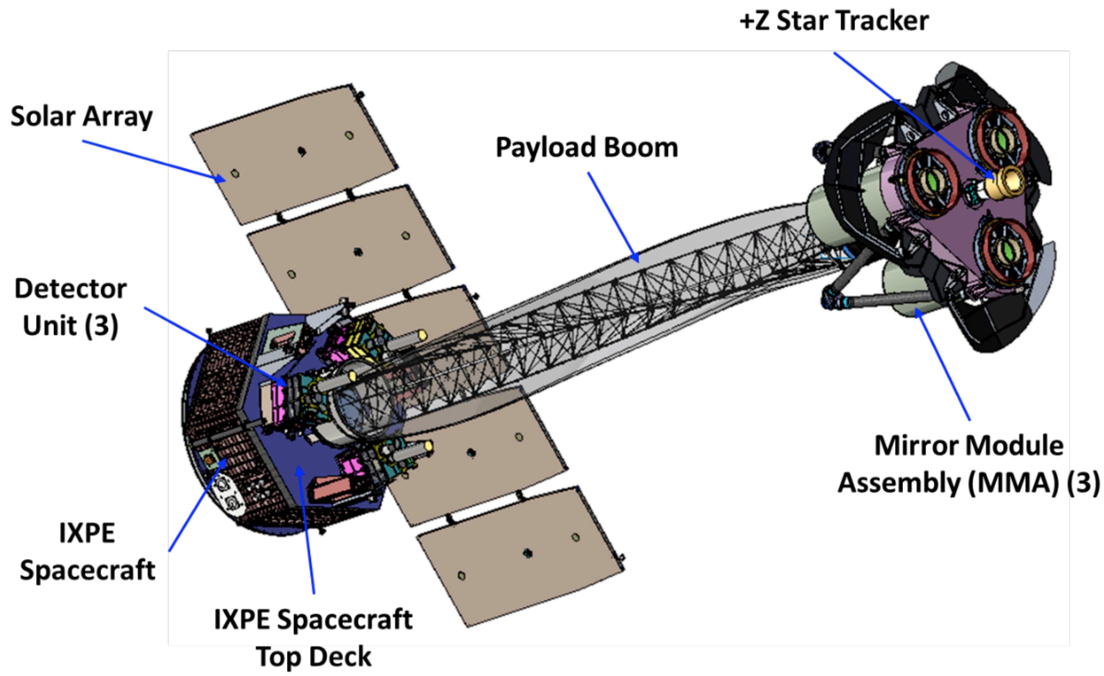

Figure 1. IXPE Deployed Observatory Includes Star Tracker Co-Aligned with Payload LoS.

obscuration.

Each DU and its associated MMA constitute an X-ray telescope with a 4-meter focal length whose LoS is defined as the ray from DU node point (defined as the center of the DU's gas pixel detector (GPD)) through the MMA's optical node (located near the MMA geometric center). Careful alignment and positioning of each MMA and DU during Payload integration and test establishes co-aligned X-ray telescopes enabling science data collection from extended X-ray sources in all three detectors simultaneously. Each telescope LoS is co-aligned with the +Z star tracker ensuring Observatory LoS pointing accuracy for science target acquisition.

ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM (ADCS)

Figure 2 shows the ADCS flight hardware complement with interfaces to the Avionics. The primary attitude sensor is a star tracker with two OH and one Electronics Unit (EU). One OH is collocated and co-aligned with the MMAs on the MMSS; X-ray telescopes are co-aligned with this star tracker OH. As such, each MMA, each X-ray telescope, and the OH LoS point along the Observatory's +z-axis. The second OH is mounted to the Spacecraft, aligned with the Observatory's -z-axis, and has an unobstructed field of view (FoV) through the launch adaptor ring and Spacecraft bottom deck. This anti-boresighted OH configuration precludes simultaneous Earth obscuration. Coarse attitude determination is provided using 12 coarse sun sensors and a three-axis magnetometer. A GPS receiver with two antennas supports continuous GPS signal availability for ephemeris and precision timing data. Three mutually orthogonal reaction wheel assemblies (RWA) accommodate environmental disturbance torques and Observatory agility requirements. Angular momentum management employs three mutually orthogonal electromagnetic torque rods with magnetometer measurements to desaturate the reaction wheels. Torque rods are sized to counter the dominant gravity gradient torque, which is driven by

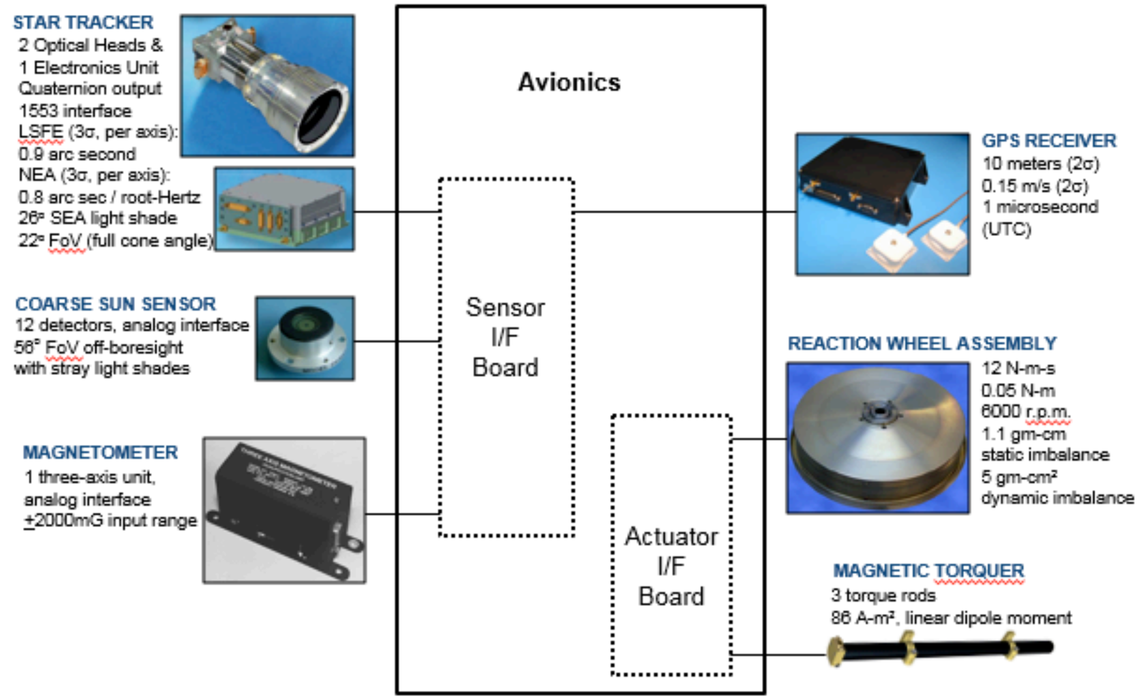

Figure 2. IXPE ADCS Component Characteristics and Interfaces to IAU.

Observatory moments of inertia. Figure 3 illustrates ADCS component locations on the Spacecraft. GPS antennas are integrated onto the +Y and -Y Spacecraft panels, enabling continuous GPS coverage throughout each orbit. The magnetometer is mounted on a post above the Spacecraft top deck to prevent saturation, accommodating relatively large torque rods on a compact Spacecraft.

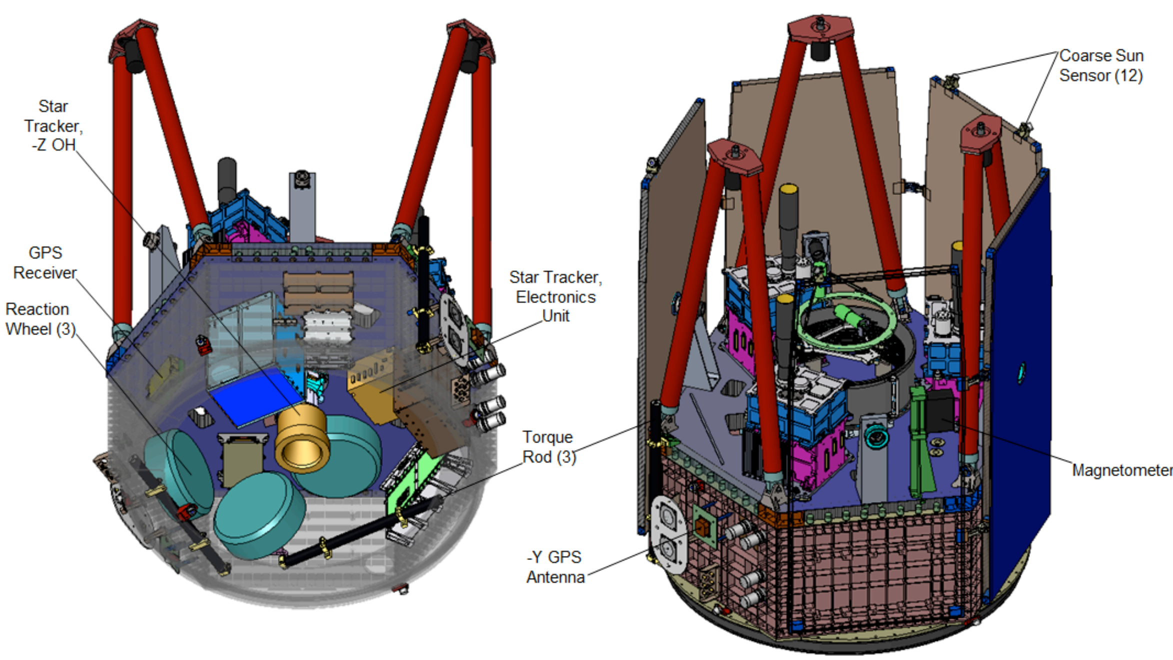

Figure 3. ADCS Component Locations in IXPE Spacecraft.

Control Loop Stability and Control-Structure Interaction

The IXPE Observatory exhibits low-frequency structural dynamic modes manifested in the deployed boom and solar array, which introduce potential for adverse interaction with the attitude control loop. Dominant flexible body modes are boom torsion at 0.43 Hz, solar array symmetric out-of-plane bending at 2.2 Hz, and boom lateral bending at 3.4 Hz.

Additionally, IXPE's star tracker and reaction wheel assembly locations produce three different sensor-actuator configurations: a non-collocated sensor-actuator set, a collocated sensor-actuator set, and collocated and non-collocated sensors together. Attitude control loop stability must be analyzed for each sensor-actuator configuration because the boom mode affects the control system differently. The non-collocated sensor-actuator configuration is the most difficult to stabilize, and so its control loop design results are summarized herein.[30]

- The primary configuration is a non-collocated sensor-actuator set (i.e., closing control loop with Payload-mounted, forward-looking star tracker OH and Spacecraft-mounted reaction wheels), which is employed during science data collection. Here, the boom flexible body mode is an "in-the-loop, non-minimum phase" mode.[31]
- The second configuration is a collocated sensor actuator set (i.e., closing loop with Spacecraft-mounted, aft-looking OH and Spacecraft-mounted reaction wheels), used during Earth occultation of the Payload-mounted star tracker OH. For this configuration, the boom mode is an "appendage" or self-stabilizing mode.
- A third configuration operates with collocated and non-collocated sensors together, and the boom mode is an "in-the-loop minimum phase mode".

Attitude control loops employ a proportional-integral-derivative (PID) compensator supplemented with a non-minimum phase (NMP) notch filter that provides gain and phase stabilization of flexible body modes. As the name suggests, the NMP notch filter's zeros are in the right-half plane, yielding additional phase roll-off for modal stabilization.[32] Attitude control algorithms are implemented at 10 Hz, and star tracker measurements transmit across the 1553 interface at 10 Hz. Computational/measurement time delays totaling 100 milliseconds are used in the analysis in addition to the 50-millisecond delay of the 10-Hz zero-order-hold (ZOH).

Figure 4 contains a color-coded image of the boom lateral bending mode (where warmer colors indicate relatively larger deflection and cooler colors indicate relatively smaller deflection) together with an annotated Nichols plot summarizing the x- and y-axis attitude control loop stability results. The boom bending mode has 60% inertia fraction due to the large deployed Payload mass. Attitude control open-loop bandwidth is set to 0.057 Hz, and the NMP notch filter is tuned such that the boom mode and the solar array mode are gain and phase stabilized over a +/-10% variation in boom modal frequency. There is a 12-dB gain margin for all structural modes.

Figure 5 presents z-axis attitude control loop stability results along with color-coded images of the boom torsion mode (on the left-hand side) and solar array mode (on the right-hand side). The boom torsion mode has 33% inertia fraction, and the solar array mode has 28% inertia fraction. The 0.013-Hz control loop bandwidth and NMP notch filter tuning provide phase stabilization and gain stabilization of the boom torsion mode over a +/-20% variation in deployed Payload inertia.

Observatory LoS Pointing and X-Ray Telescope Co-Alignment

Pointing requirements flow from the Level 1 requirement on extended object imaging. The largest extended X-ray science target is 9 arc minutes in diameter, while each DU's usable FoV

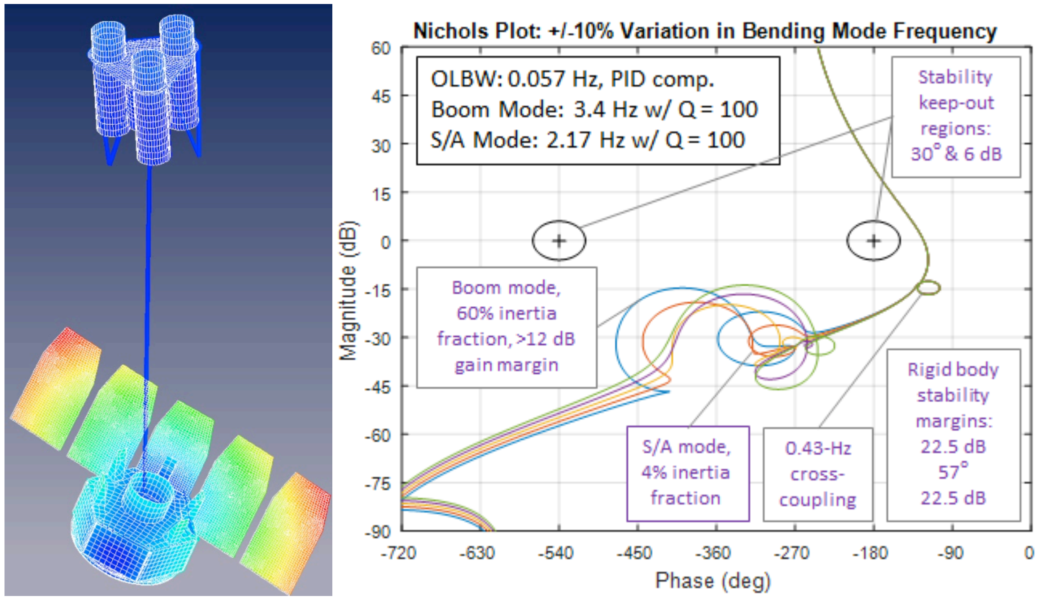

Figure 4. X- & Y-axis PID Control Loops with NMP Notch Filter Yield ≥12 dB Gain Margin and Phase Stabilize Boom Bending Mode for +/-10% Variation in Modal Frequency.

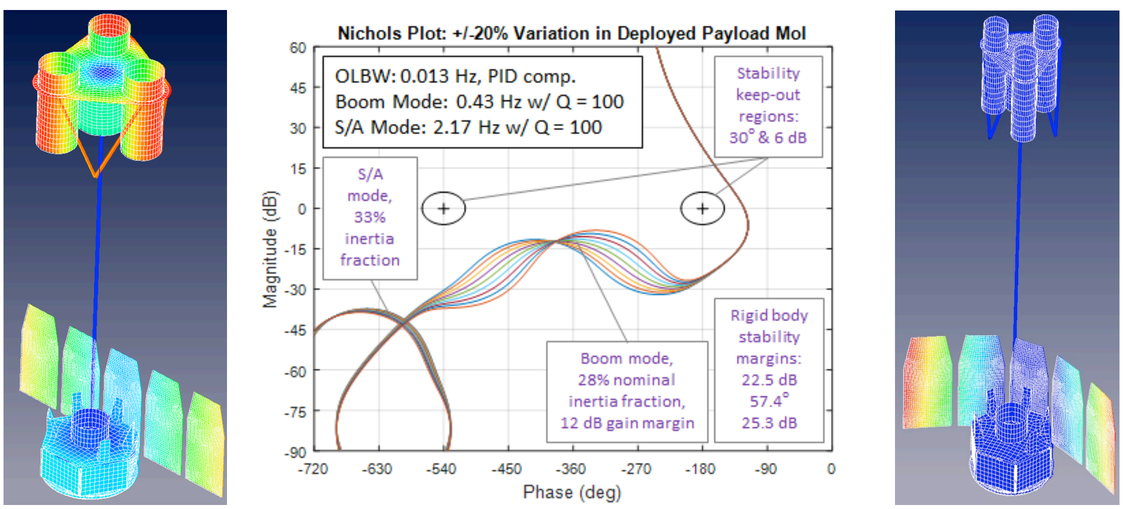

Figure 5. Z-axis PID Control Loop with NMP Notch Filter Yields ≥12 dB Gain Margin and Phase Stabilizes Boom Torsion Mode for +/-20% Variation in Deployed Payload Inertia.

has an 11-arc minute diameter yielding a 1 arc minute radial requirement. Simultaneously viewing a large extended object in all three DU FoV drives the requirement on X-ray telescope co-alignment. Figure 6 contains a notional depiction of IXPE Payload elements, illustrating the LoS for each star tracker, MMA, and X-ray telescope. The assembly and alignment sequence begins with mounting the +Z star tracker orthogonal to the MMSS plane. Next, each MMA is installed on the MMSS, aligning the MMA LoS to the star tracker LoS. Lastly, careful positioning of each DU establishes co-aligned X-ray telescopes that are aligned with the star tracker LoS, as well. This co-alignment enables science data collection from extended X-ray sources in all three X-ray detectors simultaneously and Observatory LoS pointing accuracy for science target acquisition.

The MMSS interfaces with the deployable boom through a Tip/Tilt/Rotation (TTR) mechanism to provide compensation for any boom deployment errors and relaxes some aspects of ground-based alignment. If on deployment, the X-ray image is not within the required position range of the detector node, the X-ray image can be re-aligned by using the TTR mechanism, while observing a bright source. This is possible because the forward star tracker is mounted with the optics, so that this adjustment effectively re-aligns the pointing axis with the new payload axis.

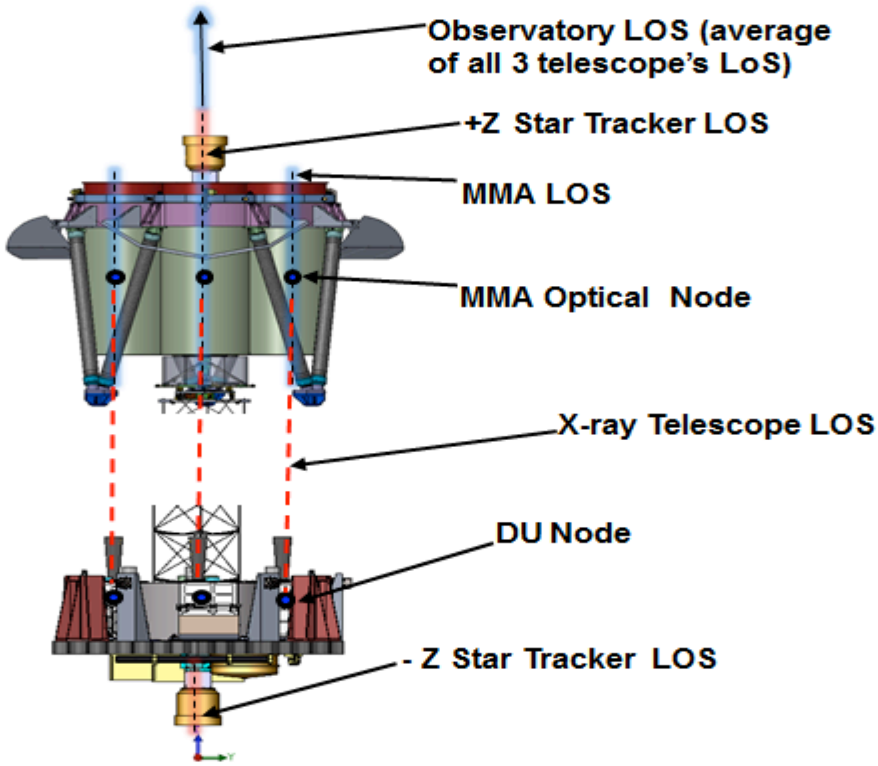

Figure 6. IXPE Payload Assembly Sequence Aligns Each MMA LoS to +Z Star Tracker LoS, Co-Aligns All 3 X-ray Telescopes, and Aligns All Telescopes to +Z Star Tracker.

Figure 7 summarizes pointing requirement flow-down into Observatory LoS pointing accuracy and X-ray telescope co-alignment accuracy. Separate budgets are maintained for LoS pointing accuracy and X-ray telescope co-alignment. Each pointing budget books error source line items under categories of biases, slowly drifting effects, and higher frequency disturbances. Key contributors that are being tracked and managed carefully are thermal distortion and positioning and alignment accuracies during integration and test.

Angular Momentum Management

Roughly 50% of the IXPE Observatory mass is deployed by the boom to establish the telescopes' 4-meter focal length. This mass distribution creates a large difference between minimum and maximum principal moments of inertia, inducing large gravity gradient torque levels for certain Observatory attitudes. Gravity gradient is the dominant environmental disturbance torque, approaching an order of magnitude larger than that from aerodynamic drag. Electromagnetic torque rod sizing accommodates environmental disturbance torque and the associated angular momentum accumulation by continuously desaturating reaction wheel assemblies while maintaining reasonable duty cycles. Reaction wheels are sized to accommodate residual angular momen-

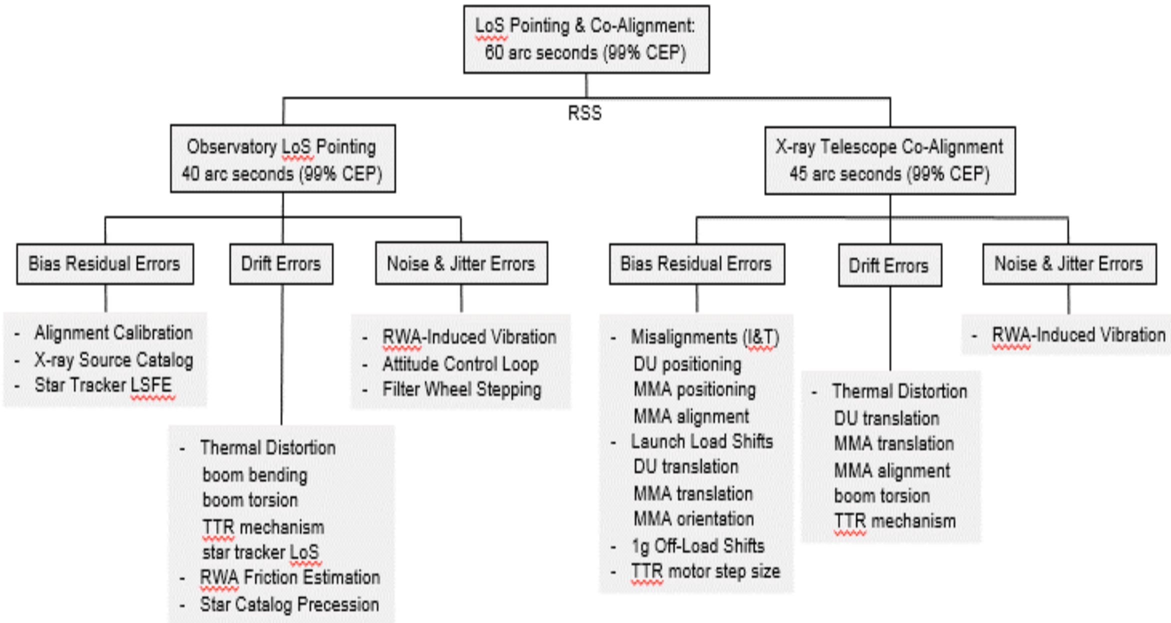

Figure 7. IXPE Observatory LoS Pointing Accuracy and X-Ray Telescope Co-Alignment Accuracy Support Extended Object Imaging in All Three DU FoV Simultaneously.

tum accumulation and Observatory retargeting agility requirements.

Figure 8 illustrates a simulated 100-orbit scenario, evaluating angular momentum management activity during a 6-day hypothetical science target observation. Observatory attitude is constant, generating gravity gradient and aerodynamic drag torque profiles that are cyclic with orbit period. This attitude is selected to maximize gravity gradient torque about Observatory x- and y-axis to model a stressing case. It produces a bias in the gravity gradient profile about Observatory x- and

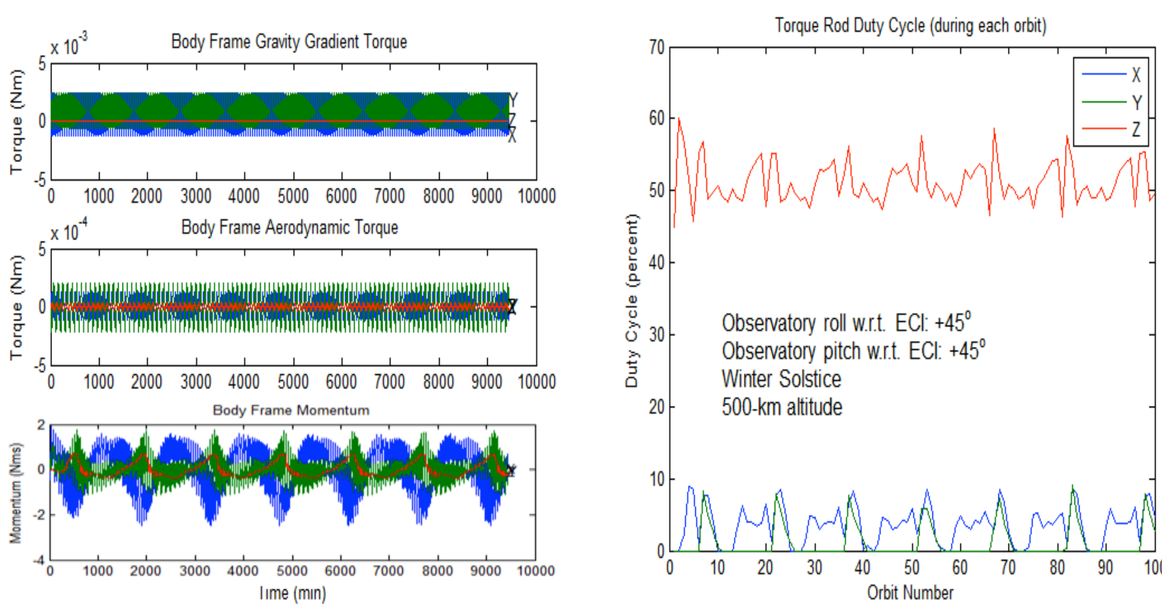

Figure 8. ADCS Actuator Sizing Accommodates Simulated Stressing Case for Angular Momentum Management Over 6-Day Science Target Observation.

y-axis. Consequently, the z-axis torque rod duty cycle is considerably higher than duty cycles of the x- and y-axis torque rods. Residual angular momentum absorbed by the reaction wheels remains within +/-2.5 Newton-meter-seconds, which is well within the reaction wheel's 12-N-m-s rated storage capacity and leaves margin for retargeting slews.

Figure 9 shows analogous simulated angular momentum management results for a second stressing Observatory attitude scenario in which gravity gradient torque is maximized about the Observatory x-axis only. Environmental disturbance torque profiles are cyclical, but a pronounced gravity gradient bias exists only about the Observatory x-axis. In response, y- and z-axis torque rod duty cycles vary between 20% and 50%, while x-axis torque rod duty cycles are less than 5%. Residual angular momentum absorbed by the reaction wheels is well within rated capacity.

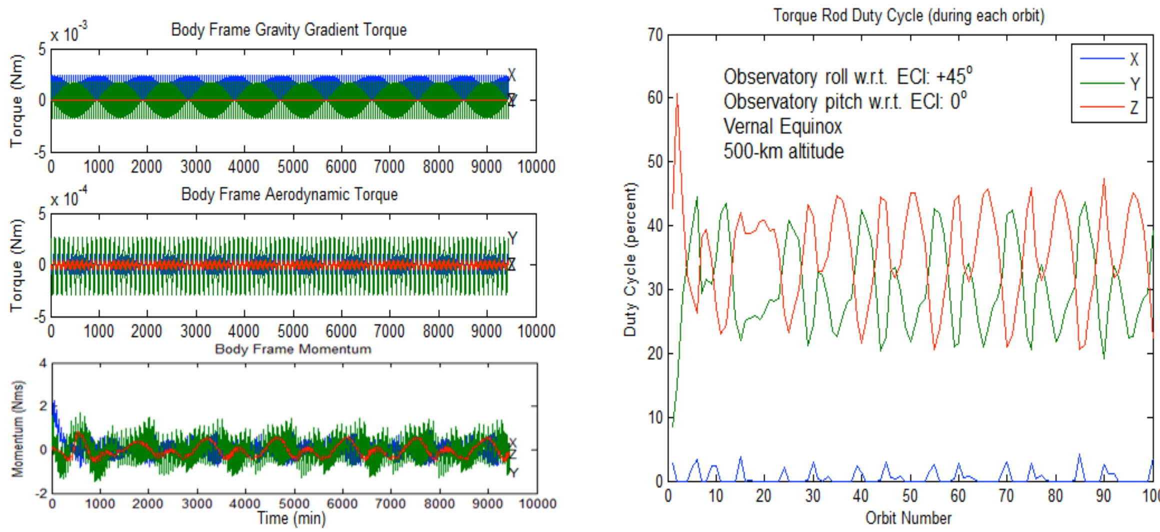

Figure 9. ADCS Actuator Sizing Accommodates Simulated Single-Axis Stressing Scenario for Angular Momentum Management Over 6-Day Science Target Observation.

CONCLUSION

IXPE brings together an international collaboration for flying an imaging X-ray polarimeter on a NASA Small Explorer. The IXPE mission will conduct X-ray polarimetry for several categories of cosmic X-ray sources from neutron stars and stellar-mass black holes, to supernova remnants, to active galactic nuclei that are likely to be X-ray polarized.

This paper summarizes the IXPE mission science objectives, the Observatory implementation, and the attitude determination and control subsystem (ADCS). It discusses three key ADCS features: (i) control-structure interaction, (ii) Observatory LoS pointing accuracy and x-ray telescope co-alignment, and (iii) angular momentum management mitigating large gravity gradient torque. ADCS analyses show the IXPE Observatory meets requirements in all cases with margin.

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