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Small Satellite Platform Imaging X-Ray Polarimetry Explorer (IXPE) Mission Concept and Implementation

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ABSTRACT

Scientists and astronomers world—wide have a great interest in exploring the hidden details of some of the most extreme and exotic astronomical objects, such as stellar and supermassive black holes, neutron stars and pulsars. However, one cannot directly image what's going on near objects like black holes and neutron stars, but studying the polarization of X-rays emitted from their surrounding environments reveals the physics of these enigmatic objects. 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." Polarization uniquely probes physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable. X-ray polarimetry is the focus of the IXPE science mission. The IXPE Observatory consists of Spacecraft and Payload modules built up in parallel to form the Observatory during system integration and test. The Payload includes three polarization sensitive, X-ray detector arrays, each paired with its corresponding grazing angle incidence mirror module assemblies (MMA). A deployable boom provides the correct separation (focal length) between the detector units (DU) and MMAs. These Payload elements are supported by the IXPE Spacecraft which is derived from the BCP-100 small Spacecraft architecture. A star tracker is a key element of the attitude determination and control system. It is mounted directly with the Payload to minimize alignment errors between the spacecraft and payload. This paper summarizes the IXPE mission science objectives and describes the Observatory implementation concept including the payload and spacecraft elements.

INTRODUCTION

IXPE is a NASA Small Explorer (SMEX) Mission.[1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] 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."

The IXPE 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), the University of Colorado, Laboratory for Atmospheric and Space Physics (CU/LASP), as well as the Italian Space Agency (ASI) with Istituto di Astrofisica e Planetologia Spaziale/Istituto Nazionale di Astrofisica (IAPS/INAF) and Istituto Nazionale di Fisica Nucleare (INFN) as major international partners.

MSFC provides the X-ray optics[14] [15] [16] [17] [18] (mirror module assemblies (MMA)) and Science Operations Center (SOC) along with mission management and systems engineering. IAPS/INAF and INFN provide the instrument consisting of unique polarization-sensitive detectors[3] [19] [20] [21] [22] [23] [24] within the detector units (DU), the detectors service unit (DSU) and interconnecting harness. 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. CU/LASP operates IXPE under contract to Ball using existing facilities similar to the way the Ball-built Kepler[25] [26] [27] and K2 missions have been operated for NASA. The IXPE Observatory communicates with the ASI-contributed Malindi ground station via S-band link. The science team generates and archives IXPE data products in HEASARC.

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. The Project entered Phase B on February 1, 2017 and completed Systems Requirements Review (SRR) in September 2017. Mission PDR occurs at the end of June 2018.

This paper summarizes the IXPE mission science objectives and describes the Observatory and payload implementation concepts at the time of mission SRR. The paper also highlights the flexibility of the Ball Configurable Platform (BCP)-100 spacecraft and its implementation for IXPE.

SCIENCE OBJECTIVES

IXPE directly supports NASA's first strategic objective in Astrophysics: "Discover how the universe works."[28] 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 our 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,"[29] also recommends such measurements.

IXPE uses X-ray polarimetry to dramatically expand X-ray observation space, which historically has been limited to imaging, spectroscopy, and timing. This advance 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 gravity, energy, electric and magnetic fields at their extreme limits.

IXPE OBSERVATORY CONCEPT

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 capturing the X-ray data from the 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 Payload 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. Changes in the IXPE orbit over mission lifetime are small, eliminating the need for a propulsion system and its resulting operational complexity. The IXPE Observatory is designed to launch on a Pegasus XL or larger launch vehicle. The IXPE Concept of Operations is summarized in Figure 1.

As noted in the literature,[7 – 11] the IXPE Spacecraft is based on Ball's BCP-100 small spacecraft product line. A view of the deployed IXPE Observatory is shown in Figure 2, while Figure 3 shows the Observatory stowed in a Pegasus XL launch vehicle fairing. When deployed, IXPE is 5.2 m in length from the bottom of the Spacecraft structure to the top of the Payload and is 1.1 m in diameter. The solar panels span 2.7 m when deployed. The Observatory launch mass is approximately 325 kg.

The Payload is mounted on the +Z face of the Spacecraft structure (top deck). This simplifies alignment and integration, and minimizes mass by providing the shortest possible load paths. The star tracker optical heads (OH) are mounted on opposite ends of the Observatory anti-boresighted from one another to prevent simultaneous Earth obscuration. One OH is mounted on top of the telescope support

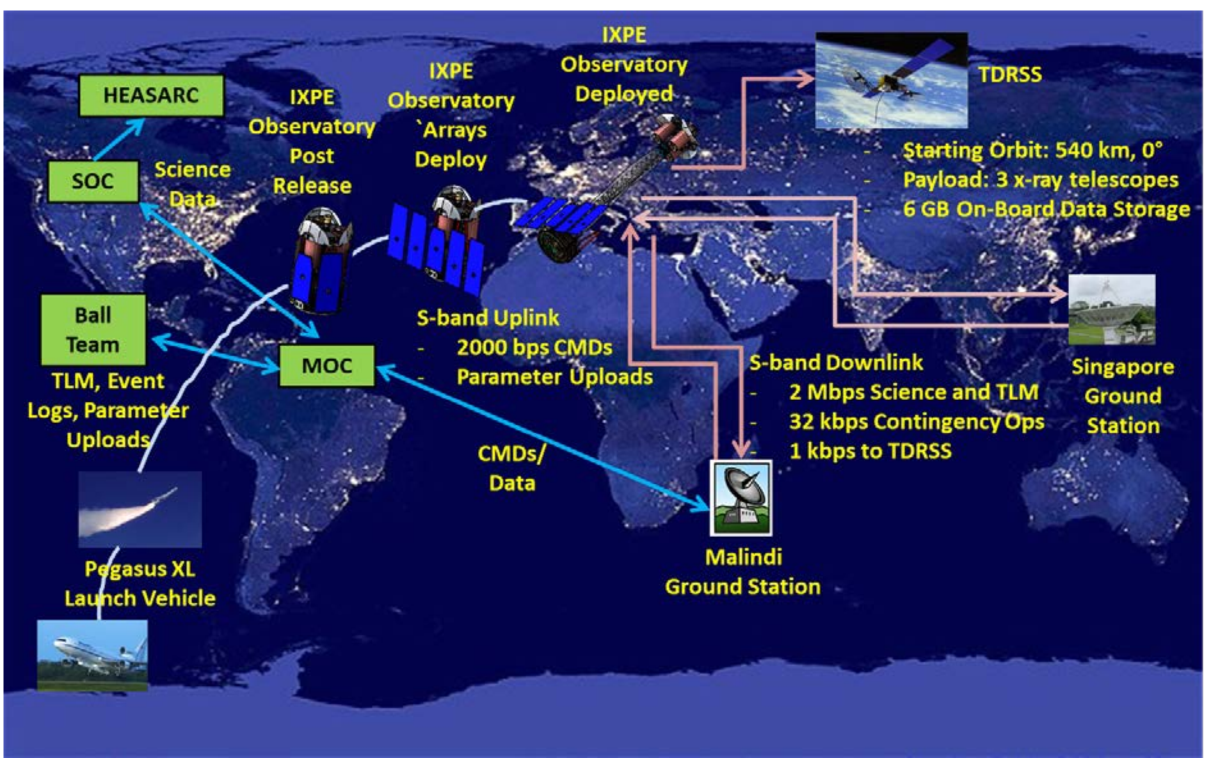

Figure 1: IXPE Concept of Operations Overview.

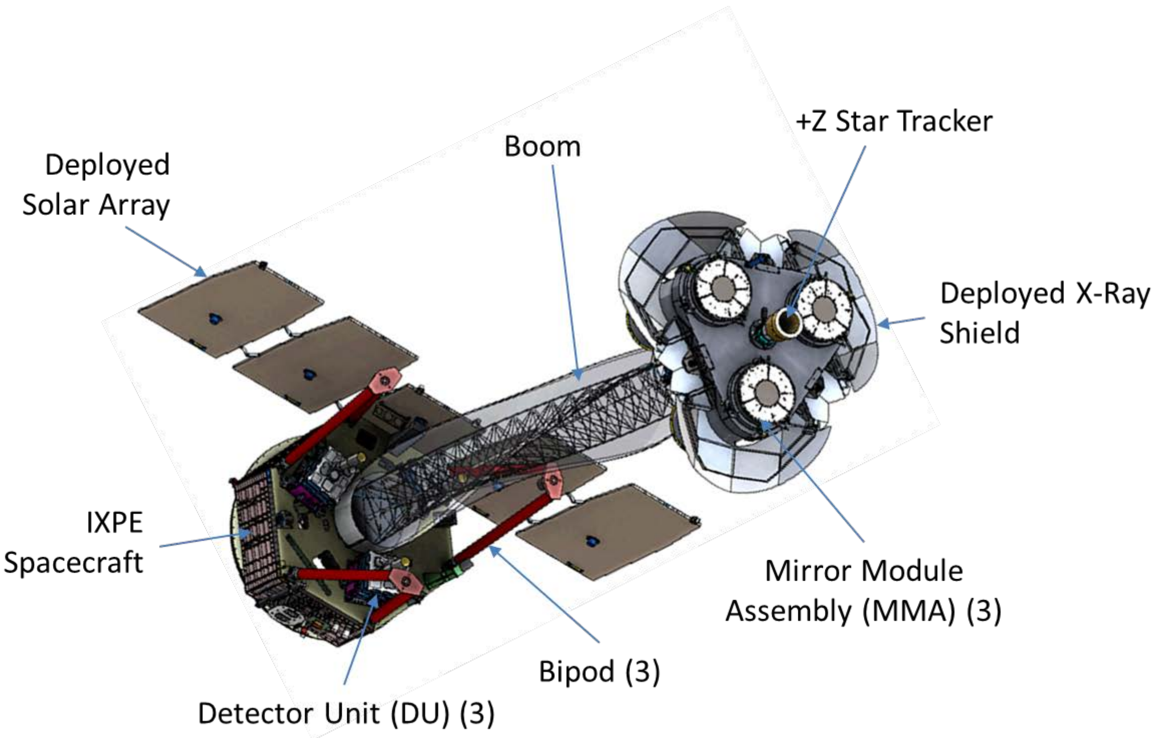

Figure 2: IXPE Observatory in its deployed configuration.

structure, co-located and boresighted with the X-ray optics. The second OH is mounted on the bottom of the Spacecraft top deck looking out through the launch adaptor ring. Two hemispherical S-band low-gain antennas are mounted on opposite sides of the Spacecraft and coupled together to provide omnidirectional communications coverage.

PAYLOAD IMPLEMENTATION

IXPE's Payload is a set of three identical, imaging, X-ray polarimetry telescopes mounted on a common optical bench and co-aligned with the pointing axis of the spacecraft.[1–11] Each system, operating independently, comprises a 4-m-focal length Mirror Module Assembly (grazing incidence X-ray optics) that focuses X-rays onto a polarization-sensitive imaging detector. The focal length is achieved using a deployable, coilable boom. Each DU contains its own electronics, which communicate with the DSU that in turn interfaces with the Spacecraft. Each DU has a multi-function filter calibration wheel (FCW) for in-flight calibration checks and source flux attenuation.

Designing an instrument of appropriate sensitivity to accomplish the science objectives summarized above involved a trade of MMA design, detector design, and the number of telescope systems, versus focal length, and considered boundary conditions of mass and power that are within Spacecraft and launch vehicle constraints. These trades were completed and the result is the three-telescope system described here which meets science objectives and requirements with margin while placing reasonable and achievable demands on the spacecraft, launch vehicle, and the deployable optical bench. Specifically, three identical systems provide redundancy, a range of detector clocking angles to mitigate against any detector biases, shorter focal length for given mirror graze angles (i.e., given energy response) and thinner/lighter, mirrors compared to a single telescope system.

Figure 4 shows the IXPE payload with key elements highlighted. The Payload uses a deployable X-ray shield to prevent off-axis X-rays from striking the detectors. The deployable boom is covered with a thermal sock to minimize temperature gradients and thermal distortion between the longerons. A metrology system, with a camera mounted on the underside of the MMSS which images a metrology target (diode string) on the spacecraft top deck, is used to monitor motions between the two ends of the Observatory during science observations. A tip/tilt/rotate mechanism allows on-orbit adjustability between the deployed X-ray optics and the Spacecraft top deck-mounted DUs, providing system tolerance to variations in deployed geometry.

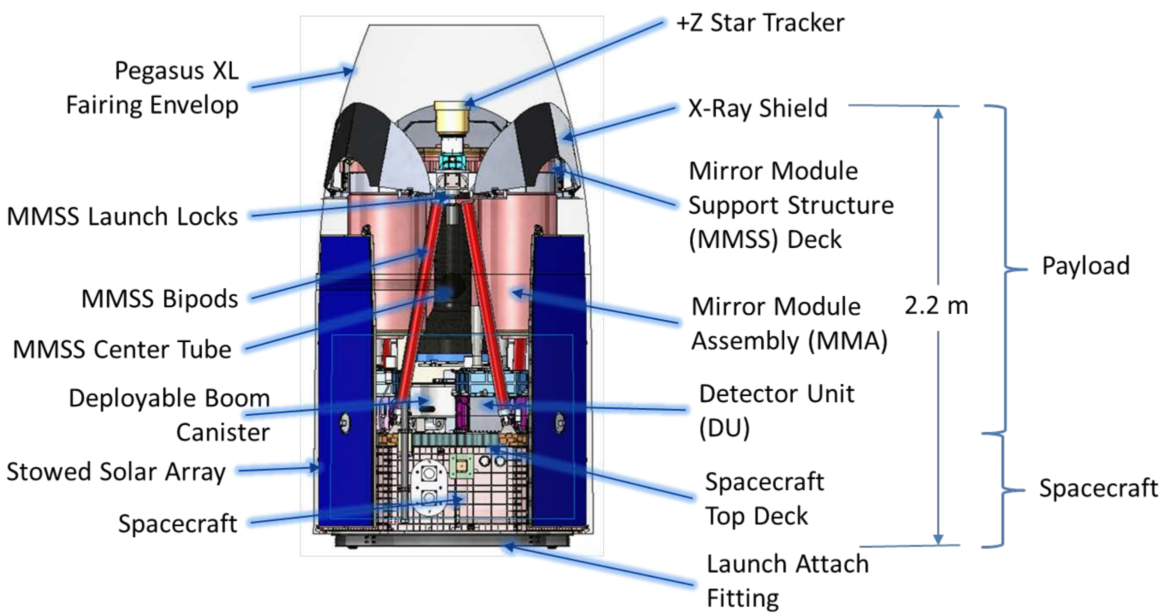

Figure 3: IXPE Observatory stowed in a Pegasus XL fairing envelope.

Mirror Module Assemblies (MMA)

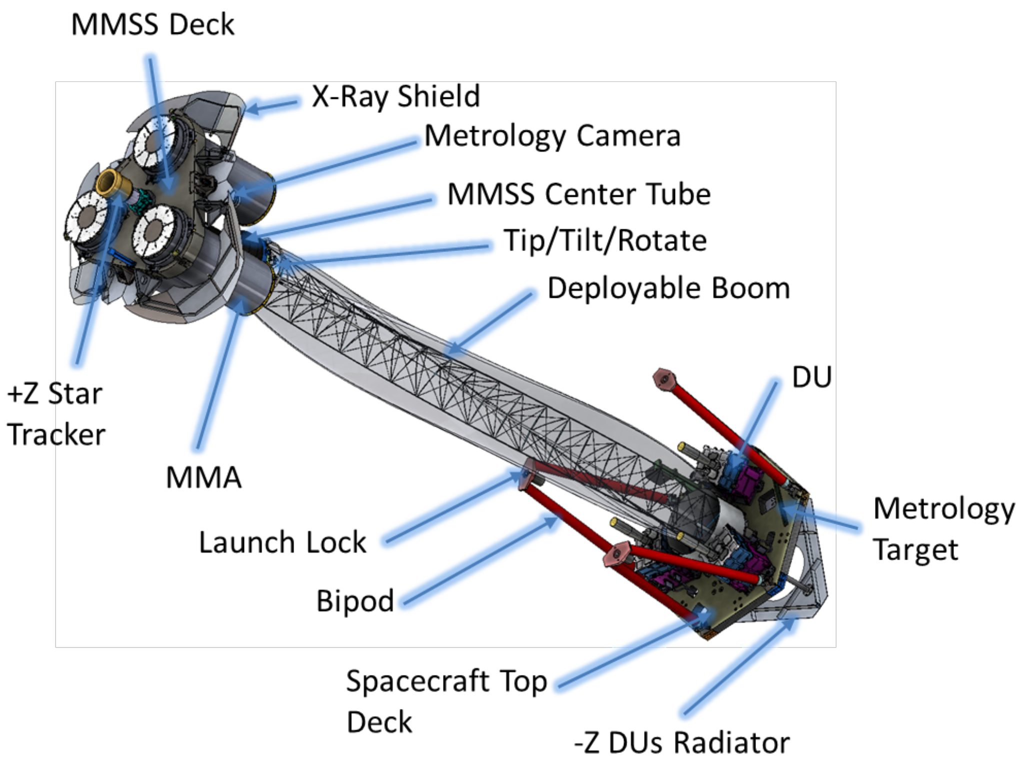

Figure 4: IXPE Payload Views Showing Key Elements; {A} Oblique Top View, {B} Oblique Bottom View.

MSFC provides grazing-incidence MMAs[14 – 18] to focus X-ray photons onto the polarization-sensitive detectors. The high-heritage IXPE design achieves 230 cm2 effective area at 2.3 keV and 249 cm2 at 4.5 keV with 24 concentrically nested X-ray-mirror shells in each 300-mm-diameter optics module. The X-ray optics deflect X-ray photons onto the detector through two grazing incidence reflections in the parabolic and hyperbolic sections. The chosen packing of the mirror shells reduces stray X-radiation impinging on the detector from sources outside the field of view (FOV) – via single reflections off the hyperbolic mirror surfaces – by more than 2.5 orders of magnitude. This ensures that observations of faint extended sources are not compromised by a nearby bright source just outside the field of view. These mirrors enable imaging, key for IXPE science, and also provide a large amount of background reduction by concentrating the source flux into a small detector area.

Instrument

The ASI-provided instrument consists of three DUs and the DSU along with the interconnecting cabling. At the very heart of each DU is a polarization-sensitive imaging detector that allows broad-band X-ray polarimetry with low net background and minimal, if any, systematic effects.[19 – 24] These Gas Pixel Detectors (GPD) were invented and developed by the Italian members of the team and refined over the past 15 years to a high level of maturity. The GPDs utilize the anisotropy of the emission direction of photoelectrons produced by polarized photons to gauge with high sensitivity the polarization state of X-rays interacting in the GPD gaseous medium. X-rays in the energy range of 2–8 keV are the focus of IXPE investigations. The GPDs are supported by electronics within the DU to operate and collect the data from the GPDs. A filer calibration wheel (FCW) is included in each DU and includes polarized and un-polarized X-ray sources to check calibration on orbit. A collimator sits on top of the DUs which, in combination with the X-ray shield around the MMAs, blocks off-axis radiation (not passing through the X-ray optics) from entering the detectors. The DSU provides the needed secondary power lines to the DUs, controls each DU, manages their FCW and high voltage operations, provides the thermal control of the GPD, collects the housekeeping, processes and formats the scientific data, and interfaces to the spacecraft avionics.

X-Ray Telescopes

The IXPE Observatory is based in three X-ray telescopes. Each telescope consists of an MMA and a DU. The MMAs and DUs are paired during calibration testing at MSFC. The defined MMA—DU pairs are then integrated and aligned at Ball as matched sets during payload integration and test. Each MMA—DU has an individual FOV of 11 arcmin. The Observatory FOV, the overlapping FOVs of the 3 telescopes, is 9 arcmin.

Metrology

An onboard metrology system is used to monitor initial on-orbit alignment positions, and residual motions of the boom for post-facto science data processing. This consists of a space-qualified Ball-built visible camera (VisCam) and several light-emitting diodes (LEDs) which form the metrology target. The camera tracks the motion of the spacecraft top deck via the relative positions of the diode array (where the DUs are mounted) with respect to the X-ray mirror platform (where the camera is mounted) in three degrees of freedom—two translational motions and rotation. This information is used in science data post-processing to help refine the specific pointing locations on the sky for the collected X-ray photons.

Payload Structures and Mechanisms

The three IXPE MMAs are mounted to a metallic mirror module support structure (MMSS) deck. The MMSS deck contains a deployable X-ray shield that, in combination with the collimator tube atop each detector, blocks virtually all X-rays from entering the detector that have not passed through the MMA. Three bipods attached to the MMSS deck support launch loads.

Additionally, the MMSS interfaces with the coilable, deployable boom[30] through a Tip/Tilt/Rotation (TTR) mechanism to provide compensation for any boom deployment errors and relaxes some aspects of on-ground alignment. If on deployment, the X-ray image is not within the required position range of the detector center point, the X-ray image can be re-aligned by using the TTR mechanism, while observing a bright source. Note that all three MMAs are moved in unison. 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. Co-alignment of the individual MMAs with respect to each other and the star tracker, is performed during payload integration and test.

SPACECRAFT IMPLEMENTATION

The IXPE Observatory is based on Ball's BCP-100 Spacecraft architecture.[31 32 33 34 35 36 37 38 39 40 41 42] The modular design allows for concurrent payload and spacecraft development with a well-defined, clean interface that reduces technical and schedule risk. The BCP-100 design supports the project goal of incorporating a low-risk spacecraft by using flight-proven components, a simple structural design, and significant design and software reuse from prior missions.

Background

The BCP-100 design is based on the US Air Force Space Test Program (STP) Standard Interface Vehicle.[31–37] The single-string design balances a low-cost and low-risk approach with significant spacecraft capability and flexibility. The BCP-100 capabilities support a variety of potential payloads. The standard spacecraft can operate over a wide range of low earth orbit altitudes (400 – 850 km) and inclinations (0º to sun-synchronous). Mission-tailored multi-layer insulation blankets for the spacecraft and payload(s) provide isolation and the appropriate radiator coverage for the particular orbit and payload suite. The star trackers are key elements of the attitude determination and control system. The forward tracker is mounted directly to payload bench to minimize alignment errors between the spacecraft and payload. The spacecraft uses non-proprietary standard Payload-to-Spacecraft interfaces (mechanical, thermal, data (RS-422) and power (28Vdc ±6 Vdc)) for straightforward accommodation of payloads. The spacecraft architecture enables a short, achievable schedule from authorization to proceed to launch readiness.

BCP-100 Applications

STP Satellite -2 (STPSat-2) (**Figure 5**) was the first use of the STP vehicle and was launched 19 November 2010 on a Minotaur IV from the Kodiak Launch Complex, Alaska. It accommodates 2 separate Payloads.[31–33] STPSat-2 continues extended operations well beyond its 13-month design life, and achieved 7 years on-orbit in December 2017.

STPSat-3 (**Figure 5**) is the second use of the STP vehicle and was launched on 19 November 2013 on a Minotaur I from NASA Wallops Flight Facility. It accommodates 6 different payloads by partitioning resources from its four payload interfaces.[34–37] The space vehicle is operating beyond its 13-month design life and achieved 4 years of on-orbit operations in December 2017.

Figure 5: STPSat-2 and STPSat-3 Space Vehicles. The first two space vehicles in the product line, designed to increase access to space for small Payloads via standardization and lower costs.

The Green Propellant Mission (GPIM) (**Figure 6**) is the third build of this Spacecraft and first with the BCP-100 moniker that signifies an established and standard Ball spacecraft product line.[38–42] The Project started in October 2012. The GPIM Space Vehicle was completed in February 2016 and placed in storage. Launch is now expected not earlier than late Summer 2018 as an auxiliary payload (ESPA-class) on the STP-2 mission on a Space X Falcon Heavy launch vehicle. The GPIM space vehicle carries the GPIM propulsion subsystem as the primary payload and three secondary payloads.

Table 1 – IXPE Observatory Capabilities.

Parameter	IXPE Capabilities
Orbit Altitude	540 km
Orbit Inclination	0°
Launch Mass (Payload + Spacecraft	~320 kg
Orbit Average Power (OAP)	286 W
LV Compatibility	Pegasus XL
Observatory Lifetime	2 years, no life-limiting consumables
Stabilization Method	3-axis
Pointing Modes	Acquire Sun State (Safe Mode), Point State (Operations Mode)
Attitude Control	40 arcsec (3σ); x- & y-axis, Point State
Bus Voltage	28 V ± 6 V
Communication Frequency	S-Band / NEN Compatible
Command Rate	2 Kbps uplink
Telemetry Rate	2 MBPS downlink
On-Board Data Storage	6 GBytes
Payload Mass	170 kg (total)
Payload Data Handling	Up to 2.0 MBPS from DSU
Payload Command/Data Interface	RS-422, discrete I/O, analog

Figure 6: GPIM Space Vehicle. The GPIM mission leverages a flight heritage BCP-100 Spacecraft and a flight demonstration AF-M315E propellant propulsion subsystem.

IXPE Spacecraft

IXPE is the fourth build of the BCP-100-class Spacecraft, leveraging the flexibility of the BCP-100 architecture to accommodate the IXPE science Payload. The spacecraft is re-configured for launch on a Pegasus XL launch vehicle with the IXPE Payload mounted on the spacecraft top deck. It uses a hexagonal spacecraft structure to provide direct launch load paths to the launch attach fitting and provide surface area for spacecraft and payload components. The stowed solar array wraps around the spacecraft body enveloping the payload during launch and prior to deployment. Figure 7 shows the spacecraft without the top deck and payload elements. Table 1 highlights the capabilities of the IXPE Spacecraft.

The IXPE spacecraft subsystems consist of command and data handling (C&DH), flight software (FSW), telecommunications, mechanical & structural, mechanisms, thermal control, attitude determination and control (ADCS), electrical power and harnessing. The IXPE C&DH subsystem consists of the integrated avionics unit and provides all C&DH functionality including FSW hosting, uplink/downlink data handling, data storage, Payload interfaces, and all electrical interfaces. The C&DH system uses a RAD750 single board computer. IXPE's telecom subsystem is built around a simple, direct-to-ground S-band architecture using omni-directional antennas, also capable of providing a downlink through TDRSS for critical events monitoring. The power system maintains positive power balance for all mission modes and orientations and is based on a simple, robust direct energy transfer architecture. The battery clamps the operating voltage. The ADCS provides a 3-axis stabilized platform controlled by reaction wheels and torque rods. The primary attitude sensor is a pair of star tracker optical heads augmented by coarse sun sensors and a magnetometer. GPS is used for timing as well as spacecraft orbital ephemeris. The thermal control

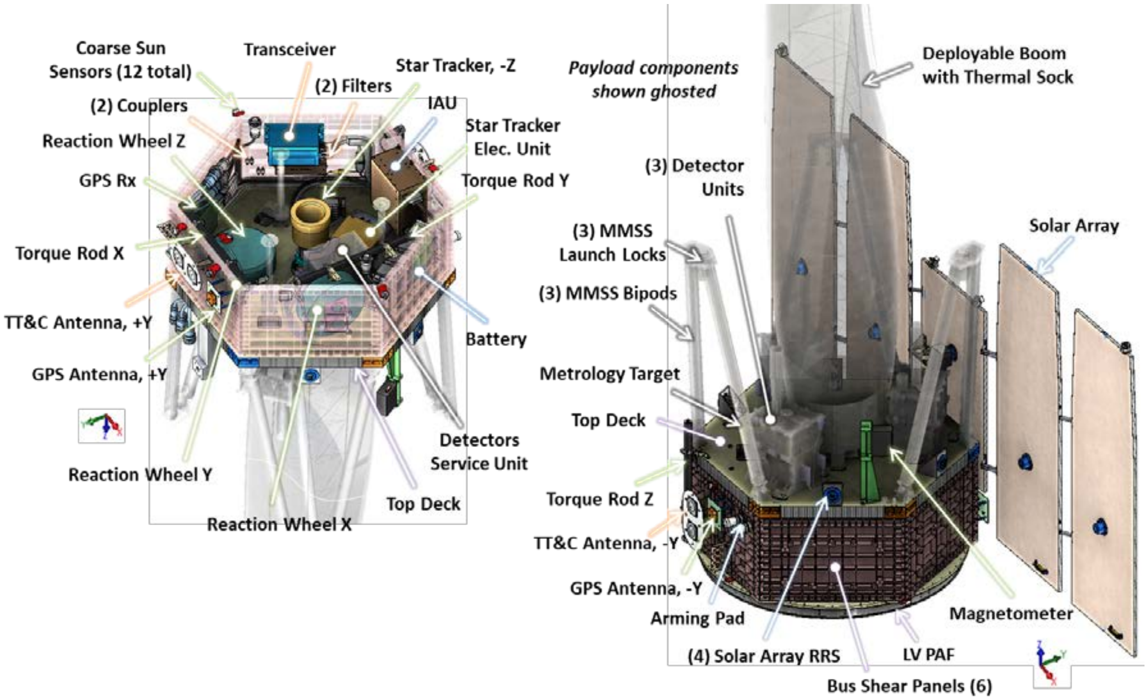

Figure 7 – IXPE Spacecraft Showing Major Elements. +Z star tracker and one coarse sun sensor are mounted on the deployed Payload.

system employs well characterized passive and active-heater thermal control to maintain all Observatory components within allowable temperatures. The spacecraft hexagonal structure is built up from machined aluminum plates and closed out with a honeycomb aluminum top deck. Spacecraft and Payload components are mounted on the internal surfaces of the spacecraft side walls and both sides of the top deck.

Mechanical Interface

The IXPE spacecraft supports a payload suite comprised of three X-ray telescopes and the supporting structure and components. Payload elements mount to the spacecraft top deck which is a honeycomb aluminum panel. The allowable payload envelope in the launch configuration is shown as part of Figure 2. Once the spacecraft is on orbit and deploys the solar arrays, payload elements are deployed or articulated as necessary to perform the mission. All deployed payload elements remain above the spacecraft top deck. The payload has an unobstructed field of regard of 2π steradian, oriented towards the +Z Observatory axis and originating at the spacecraft top deck.

Power Interface

During normal mission operations, the spacecraft generates 300 W orbit average power (OAP); the payload uses ~100 W between the different payload elements including thermal control. The payload is provided with switched power feeds. Each power feed provides unregulated 28 ±6 Vdc from the spacecraft. In addition, the spacecraft provides over-current protection on each power line provided to the payload.

Thermal Interface

The spacecraft monitors and controls the temperature of selected payload element interfaces using temperature sensors and heaters mounted to the spacecraft top deck and distributed among the payload elements. The spacecraft top deck is maintained at a temperature of 20ºC ±5ºC supporting the DUs. The MMAs are maintained to a fairly tight tolerance of 20ºC ±5ºC. FSW-controlled heaters maintain the MMAs, DUs, MMSS deck and spacecraft panels at stable temperatures throughout the orbit and seasonal changes to minimize distortions along the telescopes lines of sight. The temperature measurements are provided to the ground as part of spacecraft state of health (SOH) data.

Data Interfaces

The spacecraft avionics provides the main data, command and power interfaces with the payload. All payload command, data collection, and data storage is through a payload interface card which resides within the avionics. The payload interface provides the Payload with a set of data ports for commands, and collection of high rate data, real-time data, analogs and discretes.

Both the payload high rate and real-time data are time-stamped based on a 1-PPS signal from the GPS receiver and provide accurate time knowledge of the detected X-ray photons and corresponding ancillary data. The payload interface ingests payload high rate mission data, encapsulates this data in a Consultative Committee for Space Data Systems (CCSDS) compliant Channel Access Data Unit (CADU) format and stores the formatted CADU for subsequent transmission to the ground. All high rate data is transferred via a synchronous EIA compliant RS-422 link. The total high data rate available is 2 Mbps. The Payload interface provides total mass memory storage of 6 GBytes of error detection and correction (EDAC)-validated memory space.

The Payload interface provides for collection of Payload real-time data via an EIA-422 UART Payload data port. Payload real-time data is collected and interleaved into the real-time Spacecraft downlink and is also stored in the avionics for retransmit.

CONCLUSION

IXPE brings together an international collaboration for flying an imaging X-ray polarimeter on a NASA Small Explorer. IXPE 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 summarized the IXPE mission science objectives and the Observatory and payload implementation concept. An overview of the novel Ball BCP-100 small spacecraft was given followed by a description of the IXPE spacecraft. The Project kicked off in February 2017. Mission SRR occurred in September 2017. The Spacecraft PDR occurred March 20, 2018. Near-term milestones include Payload PDR on April 24, 2018, Instrument CDR in May 2018 and Mission PDR in June 2018. Mission launch is planned for April 2021.

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