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The Small Satellite-Based, Imaging X-Ray Polarimeter Explorer (IXPE) Mission

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ABSTRACT

The Imaging X-ray Polarimeter Explorer (IXPE) focuses on high energy astrophysics in the 2—8 keV x-ray band. IXPE is designed to explore general relativistic and quantum physics effects of gravity, energy, electric and magnetic fields at extreme limits. IXPE, a NASA Small Explorer (SMEX) Mission, will add new dimensions to on-orbit x-ray science: polarization degree, polarization angle and extended object polarization imaging. Polarization uniquely probes physical anisotropies that are not otherwise measurable—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin. Detailed imaging enables the specific properties of extended x-ray sources to be differentiated. 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 paired with three x-ray mirror module assemblies (MMA). A deployable boom provides the correct separation (focal length) between the detector units and MMAs. Currently, the boom has been delivered, all four detectors units (DU) are complete, the detectors service unit (DSU) is complete, instrument system testing has been completed (DSU with 3 DUs), three of four MMAs is built and all spacecraft components except the solar array have been delivered along with the spacecraft and payload structures. Payload and spacecraft integration and test (I&T) started in March 2020. This paper overviews the flight segment (the Observatory, payload, and spacecraft implementation concepts) with emphasis on the build status and summarizes the launch segment. Launch is planned to occur on a Falcon 9 launch vehicle during Summer 2021. The paper summarizes the impacts of switching from the 'design-to baseline' of Pegasus XL to the selected launch vehicle for flight, Falcon 9. COVID-19 impacts to the Project are also summarized. The paper will close with a summary of the mission development status. The Project is firmly into the build phase for both the spacecraft and payload and rapidly approaching Observatory I&T.

INTRODUCTION

Scientists 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, pulsars and other neutron stars. However, it is not possible to 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 can reveal some of the details of the physics of these enigmatic objects. The goal of IXPE is to expand understanding of high-energy astrophysical processes and sources.

The IXPE NASA Small Explorer (SMEX) Mission [1-9] 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 di Astrofisica e Planetologia

Spaziali/Istituto Nazionale di Astrofisica (IAPS/INAF), Istituto Nazionale di Fisica Nucleare (INFN) and OHB-I as major international partners, **Figure 1**.

Figure 1: The International Team Executing the IXPE Mission Takes Advantage of Team Member Expertise

MSFC provides the grazing-incidence x-ray mirror module assemblies (MMA) [10-13] and the Science Operations Center (SOC) along with mission management and systems engineering. IAPS/INAF, INFN and OHB-I provide the unique polarization-sensitive detector units (DU) [2,4,14-17] and the detectors service unit (DSU) as part of the Italian Space Agency (ASI) contribution. ASI will also provide the primary ground station, located in Malindi (Kenya). Ball is responsible for the spacecraft, payload mechanical elements along with payload, spacecraft and System I&T followed by launch and operations. The Mission Operations Center (MOC) is located at CU/LASP and will be operated similar to Kepler/K2 mission [18-20]. The Science Operation Center is located at MSFC with a participation of the ASI Space Science Data Center (SSDC).

This paper builds on three prior IXPE Mission and Observatory papers at previous USU Small Sat Conferences [5-7]. This paper overviews the mission concept of operations (**Figure 2**), the flight segment (the Observatory, payload, and spacecraft implementation concepts) with emphasis on the build status including the launch segment. Launch is planned to occur on a Falcon 9 launch vehicle in 2021. The paper covers the impacts of switching from the 'design-to baseline' of Pegasus XL to the selected launch vehicle for flight, Falcon 9. COVID-19 impacts to the Project are also summarized. The paper will close with a summary of the mission development status.

IXPE OBSERVATORY CONCEPT

IXPE is designed as a 2-year mission with possible extension as a general-observer mission. IXPE launches to a circular low Earth orbit (LEO) at an altitude of 600

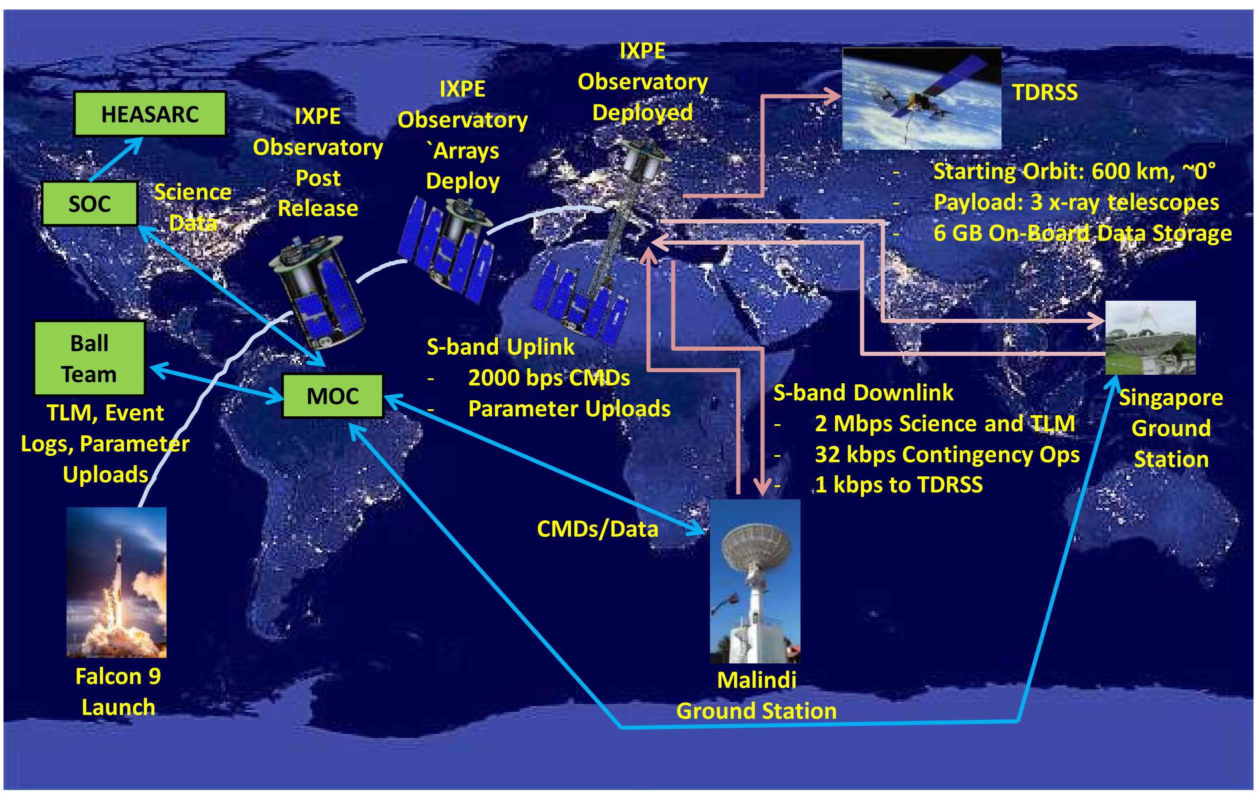

Figure 2: IXPE Concept of Operations Overview

km and an inclination of 0.2 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 up to many days at a time.

The Observatory is designed to support IXPE science and measurement requirements. These requirements have been stable since mission selection. 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 ±25° 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.

The IXPE Observatory is designed to launch on a Pegasus XL or larger launch vehicle. In July 2019, a Falcon 9 launch vehicle was selected to launch IXPE. **Figure 3** shows the Observatory in its stowed configuration and within the Falcon 9 launch vehicle fairing compared to the Pegasus XL fairing. **Table 1** provides a summary of key design updates and changes made since the selection of the Falcon 9 launch vehicle for IXPE.

A view of the deployed IXPE Observatory is shown in **Figure 4**. When deployed, IXPE is 5.2 m 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 340 kg. As noted in the literature [5-9] the IXPE spacecraft is based on Ball's BCP-small spacecraft product line.

Table 1: IXPE Observatory Key Updates: Designed for Pegasus XL; Falcon 9 Launch Vehicle Selected

Design Change/Update	Result
Launch Induced Environments	Launch vehicle environments (random and sine vibration, shock, acoustics, EMI/EMC
Battery Arming Variations	Transitioned from battery arming plugs to use of a battery arming relay assembly
Launch Site	Launch from KSC instead of RTS (with VAFB Processing)
Higher Final Orbit	600 km ±15 km (versus 540 km ±10 km insertion apse; ±80 km non-insertion apse)
Moved to Fixed X-Ray Shields	Eliminate deployment mechanisms and associated testing; mass reduction; no longer fit in Pegasus XL fairing

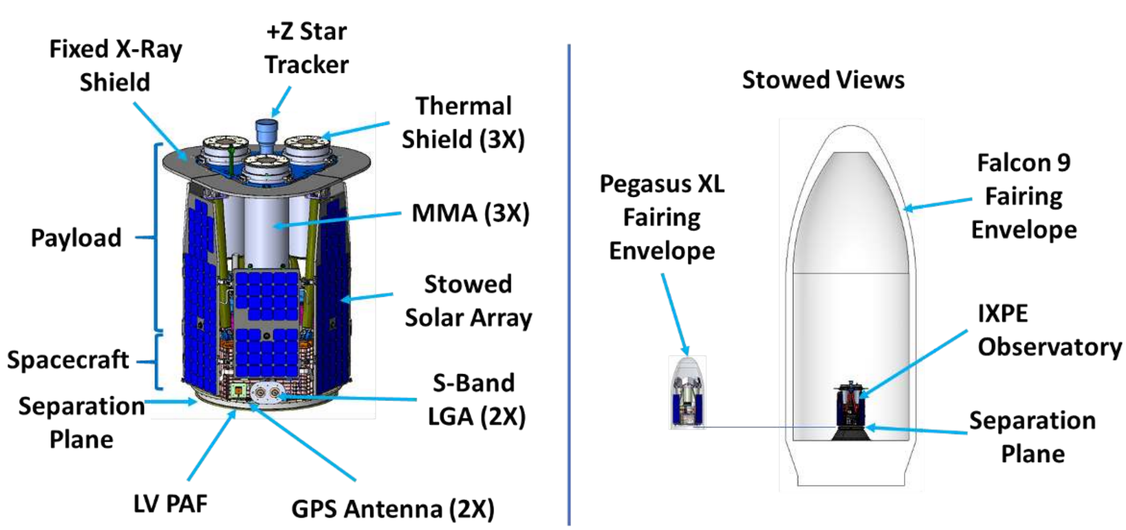

Figure 3: IXPE Observatory Stowed Configuration; in Pegasus XL and Falcon 9 Fairing Envelops – Fairing fill fraction went from 99% to 7%

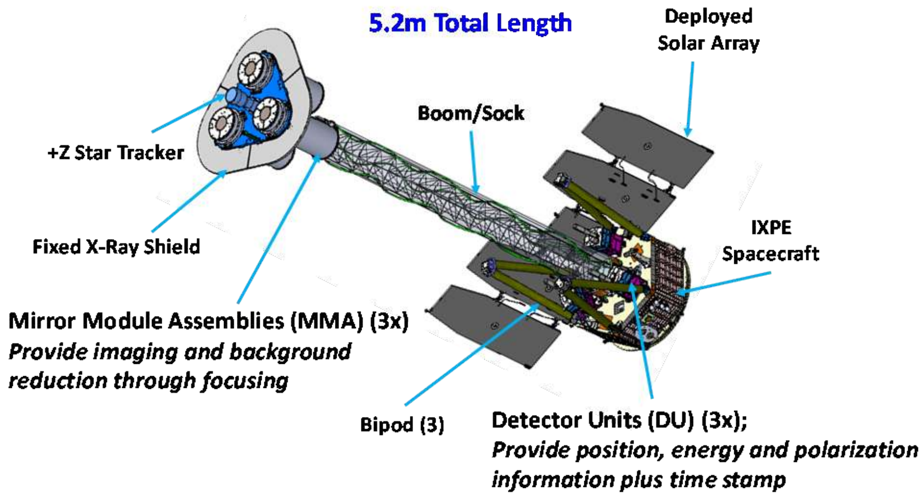

Figure 4: IXPE Observatory In Its Deployed, Science Operating Mode Configuration

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 boom deploys to provide the correct separation between the MMAs and DUs.[21] 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 MMA support structure, co-located and bore-sighted 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 (LGA) are mounted on opposite sides of the Spacecraft and coupled together to provide omnidirectional communications coverage. Two GPS antennas are also mounted on the opposite sides of the spacecraft to enable continuous GPS coverage.

The mission is operated by LASP under contract to Ball using existing facilities, similar to the way the Ball-built Kepler [18-20] and K2 missions have been operated for NASA. The IXPE Observatory communicates with the ASI-contributed Malindi ground station via S-band link while the NEN station in Singapore is used as backup. The Science Operations Center (SOC) generates IXPE data products and then archives them in High Energy Astrophysics Scientific Archive Research Center (HEASARC).

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 [1-9,21-24]. Each 4-m focal length telescope operates independently and is comprised of an MMA (grazing-incidence x-ray optics) and a polarization-sensitive, gas pixel detector (GPD)-based, imaging DU. The focal length is achieved using a deployable, coilable boom [25]. The MMAs and DUs are paired. One telescope will undergo full calibration testing at MSFC.[26] The defined MMA—DU pairs are 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. Each DU contains its own back-end electronics, which communicate with the DSU, which in turn interfaces with the spacecraft. Each DU has a multi-function filter calibration wheel (FCW) assembly for in-flight calibration checks and source flux attenuation.

Designing a payload of appropriate sensitivity to accomplish the science objectives summarized above involved a trade of MMA design, detector design, and number of telescope systems versus focal length and boundary conditions for mass and power within spacecraft and launch vehicle constraints. These trades were completed and resulted in 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 telescope systems provide redundancy, a range of detector clocking angles to minimize 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 5** highlights the IXPE key payload elements.

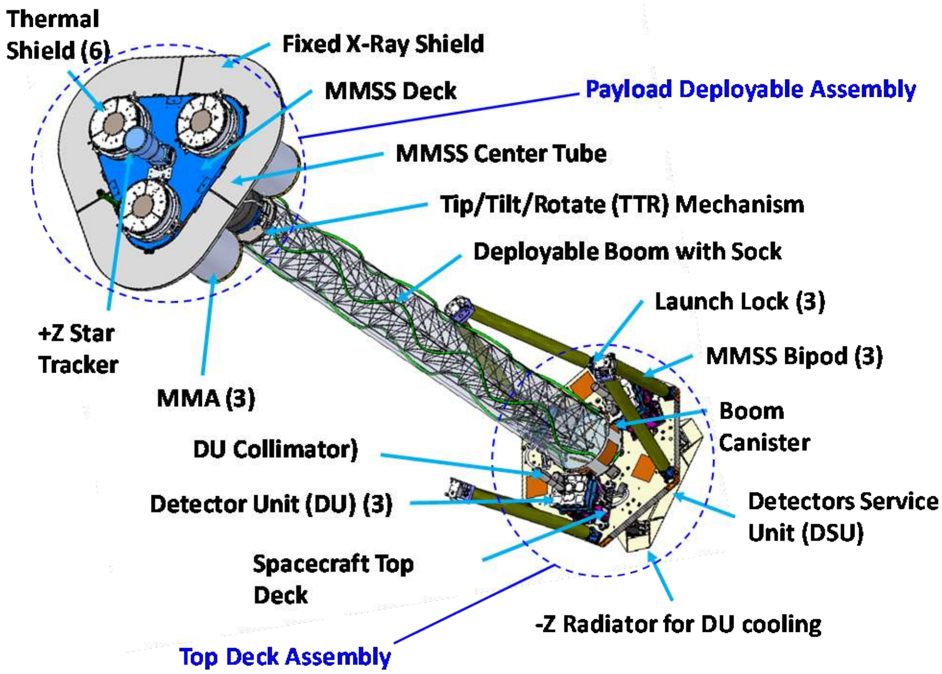

Figure 5: IXPE Oblique Top Payload View Showing Key Payload Elements

The use of a Falcon 9 LV enabled the replacement of deployed x-ray shields with fixed x-ray shields. The payload uses a fixed x-ray shield to prevent non-imaged x-rays from striking the detectors and works in conjunction with the collimators on the DUs. The deployable boom is covered with a 2-layer, thermal sock to minimize temperature gradients and thermal

distortion between the longerons. A tip/tilt/rotate (TTR) mechanism allows on-orbit adjustability between the deployed x-ray optics and the spacecraft top deck-mounted DUs. The TTR provides compensation for any boom deployment errors and enables relaxation of 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 x-ray point source. Home position indicators in the TTR mechanism serve as a reference for TTR activations. Note that all three MMAs are moved in unison. This is possible because the forward star tracker is mounted so that it aligns with the optics. Therefore, this adjustment effectively re-aligns the pointing axis with the new payload axis.

The common optical bench is the aluminum mirror module support structure (MMSS) deck and composite center tube. The MMSS deck hosts the fixed x-ray shield, MMAs and +Z star tracker. Three hinged bipods are attached to the spacecraft top deck to support launch loads of the MMSS deck through the primary spacecraft structural joints. The boom launch locks are on the upper bipod brackets at the MMSS deck interface. Upon activation of the launch locks, the bipods move outward 12° on spring-loaded hinges to provide clearance for payload elements as the boom deploys.

SPACECRAFT IMPLEMENTATION

The IXPE Observatory is based on the BCP-small spacecraft architecture [5-9] described elsewhere [27-34]. The BCP-small architecture is used for the currently operating STPSat-2 [27,28], STPSat-3 [29-31], and the recently launched NASA Green Propellant Infusion Mission (GPIM) [32-34]. The GPIM Space Vehicle was completed in February 2016, was in storage for >3 years and launched in June 2019 as an auxiliary Payload (ESPA-class) on the STP-2 mission, using a Space X Falcon Heavy launch vehicle.

IXPE is the fourth build of a BCP-small spacecraft. IXPE is leveraging the flexibility of the BCP-small architecture to accommodate the IXPE science payload. The spacecraft is re-configured to support 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.

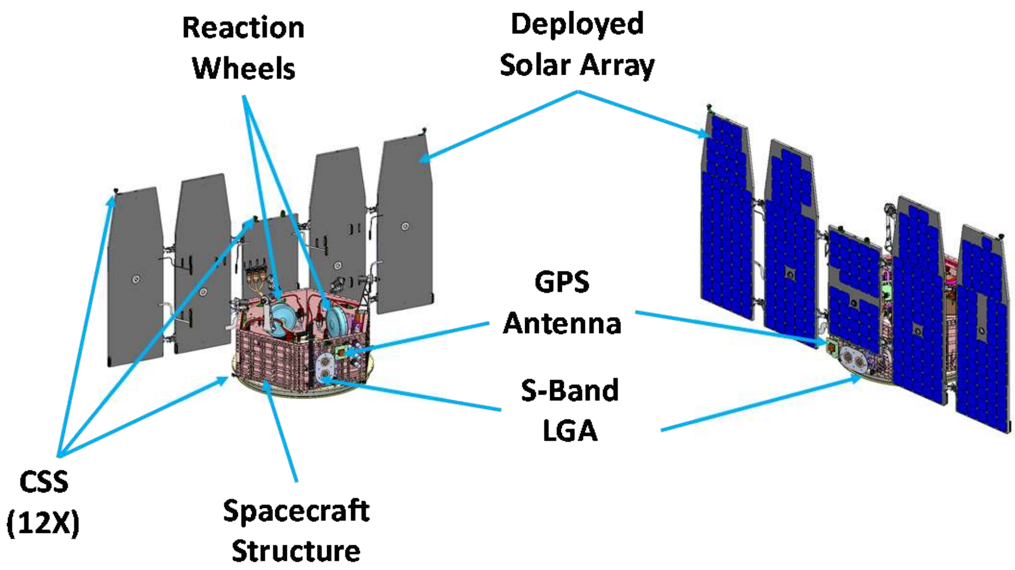

Figure 6: IXPE Spacecraft Overview. Several Spacecraft Elements Mounted on the Deployed Payload Assembly (+Z star tracker, +Z coarse sun sensor (CSS), magnetometer)

Table 2: IXPE Spacecraft Capabilities Are Based On The BCP-Small Capabilities

Parameter	Performance
Orbit Altitude	600 km
Orbit Inclination	0.2°
Launch and Commissioning	1 month – umbilical sep to entry into science ops
Launch Mass	~340 kg
Orbit Ave Power (OAP) (EOL)	306 W (EOL)
Launch Vehicle	Falcon 9
SV Lifetime	2 years, no life-limiting consumables
Stabilization Method	3-axis
Pointing Modes	Acquire Sun (Safe Mode), Point (Operations Mode)
Attitude Control	40 arcsec (3σ); x- & y-axis, Point State
Bus Voltage	30 V ± 4 V
Communication Freq.	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 CMD & Data I/F	RS-422, discrete I/O, analog

The stowed solar array wraps around the spacecraft body enveloping the payload during launch and prior to deployment (**Figure 2**). **Table 2** highlights the capabilities of the IXPE spacecraft. **Figure 6** shows the spacecraft layout.

The IXPE spacecraft subsystems consist of command and data handling (C&DH), flight software (FSW), telecommunications, attitude determination and control (ADCS), mechanical/ structural, mechanisms, thermal control, 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. IXPE's telecom subsystem is built around a simple, direct-to-ground S-band architecture using omni-directional, low gain antennas (LGA). It is 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, direct energy transfer architecture. The battery clamps the operating voltage. The thermal control 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.

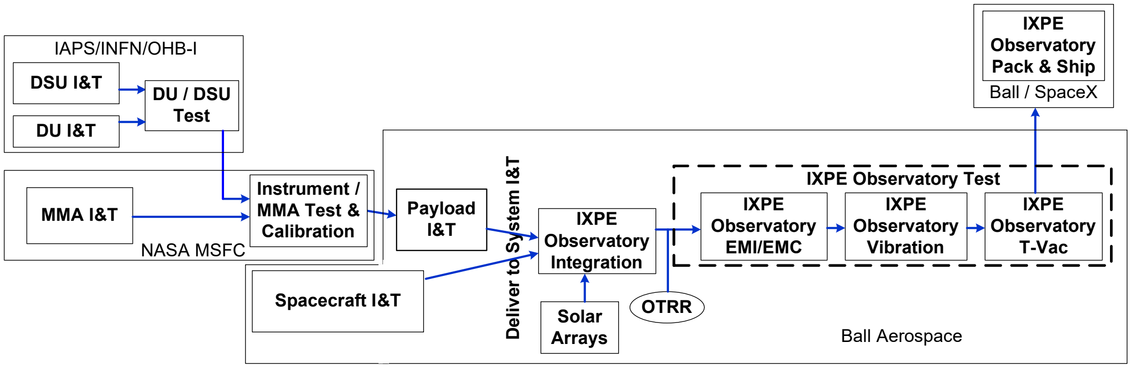

Figure 7: IXPE Observatory – IXPE Payload, Spacecraft and Observatory Integration and Test Flow

AI&T SUMMARY AND STATUS

Flight element integration and test (I&T) has started on the IXPE Project. **Figure 7** shows the top level I&T flow. All components for the spacecraft have been ordered with all components delivered at this point except the solar array. Flight builds for the payload components are underway. The flight boom/TTR is complete and delivered to Ball, **Figure 8**.

Figure 8: IXPE Flight Boom, First Deployment at Ball

The instrument work is currently finishing up at INFN, INAF/IAPS and OHB-I in Italy. All four flight DUs (including 1 spare) are complete. GSE/EGSE is complete. Calibration of all DUs are complete. The build of the flight DSU is complete along with the harnessing. End-to-end testing with the flight DSU and 3 flight DUs is complete. The remaining flight elements of the instrument are ready for shipment to Ball for I&T. The spare DU along with its EGSE will be used in detailed, telescope-level, calibration testing with the spare MMA (telescope-level) at MSFC.

The MMAs are being built by a dedicated team at MSFC. EM work has been completed. The mirror shells are manufactured by MSFC while most of the other MMA components are fabricated under contract. All MMA GSE is complete. All flight mirror shells are complete. Flight MMA assembly is well along with three MMAs complete at this time and the final shells being installed on the spare MMA. The 3 flight MMAs are awaiting environmental testing and x-ray calibration.

The payload mechanical assemblies are largely complete. The MMSS deck and composite center tube are bonded to form the optical bench. The three hinged bipods are attached to the spacecraft top deck to support launch loads of the MMSS deck through the primary spacecraft structural joints, **Figure 9**. The MMSS deck hosts the fixed x-ray shield, MMAs and +Z star tracker.

Figure 9: IXPE MMSS Deck Attached to Center-tube on Spacecraft Top Deck and Bipods Assemblies

The instrument is to be installed on the spacecraft top deck along with the boom/TTR. The MMAs are to be installed into the MMSS deck and aligned with the +Z star tracker. Alignments between the +Z star tracker, MMAs and DUs are critical to ensure accurate pointing and science data collection.

Spacecraft I&T runs in parallel to payload I&T and starts with harness, C&DH and battery installation. All spacecraft components are now mounted on the spacecraft hexagonal structure, **Figure 10**. Flight software build number one is complete. Other flight elements are integrated as available.

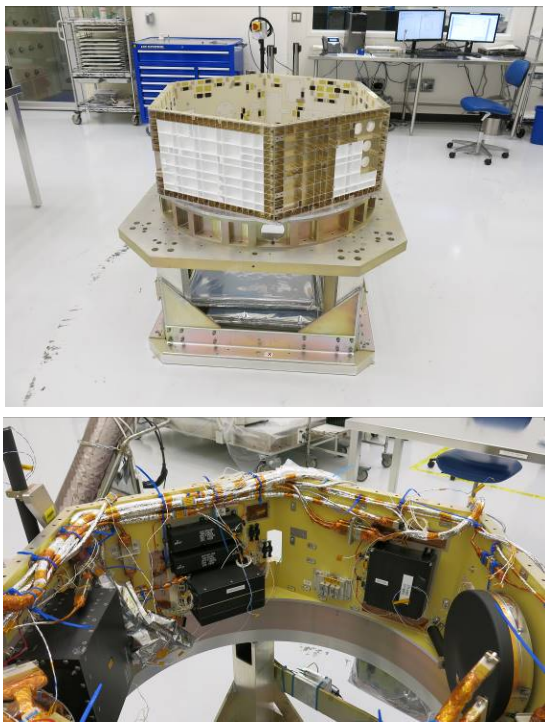

Figure 10: IXPE Completed Spacecraft Hexagonal Structure with the Top Deck on a Work Stand and without Top Deck Showing Installed Components

The payload and spacecraft modules are brought together to form the IXPE Observatory. The Observatory undergoes environmental testing. The Observatory and GSE is then shipped to KSC for launch prep and launch.

COVID 19 PROJECT IMPACTS

The world-wide pandemic caused by the novel corona virus has impacted IXPE Mission development.

I2T just completed instrument build and test as the national shutdown in Italy started. They were able to ship FM DU2 and the EM DU with EGSE prior to the shutdown orders took effect. The shutdown orders prevented I2T from completing the packing and shipping the remaining 3 flight DUs, DSU and cabling to the US. I2T is ready to ship the final instrument elements once safe and timely international shipping can be assured again. This has resulted in a multi-month delay in instrument delivery for AI&T at Ball.

MSFC is a NASA center subject to the shutdown orders levied by NASA. NASA centers were largely placed on what's known as a Level 4 closure including MSFC – nearly all on site work was stopped and nearly all personnel were not allowed on site. The Level 4 closure orders are being lifted at the time of this writing (end of May 2020) and work at MSFC is resuming on a task by task basis with approval. Approval has been granted to resume building flight MMAs #1 and #3 and prepare for calibration activities. This has resulted in a multi-month delay in MMA delivery for AI&T at Ball.

Ongoing travel restrictions for both NASA personnel and Italy in general have resulted in assignment of instrument efforts in the US to be performed by Ball. Ball will now be responsible for instrument receipt, unpacking, instrument checkout and calibration support at MSFC. Remote training by I2T is planned for June 2020. Instrument integration onto the IXPE payload assembly occurs once I2T's training process for Ball is complete and the flight instrument goes through its bench checkout.

PROJECT STATUS

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 the systems requirements review (SRR) in September 2017.

Spacecraft's preliminary design review (PDR) occurred in March 2018 followed by Payload PDR in April 2018. In parallel, the Instrument PDR occurred in early March 2018 while the Instrument CDR occurred in May 2018, both convened by ASI. Mission PDR occurred in June 2018.

IXPE is now deep into Phase C activities with Ground System PDR completed in March 2019. All major procurements are largely complete; most hardware deliveries have been received. The Mission CDR was completed in June 2019 and the Falcon 9 was selected as the launch vehicle in July 2019. Ground System CDR occurred successfully in November 2019. Focused V&V work is ongoing. [35] Spacecraft and Payload I&T started in March 2020. Spacecraft integration is now largely complete with initial spacecraft power on planned for mid-June 2020. Payload integration is largely complete. Ball is waiting for instrument and MMA deliveries. Observatory integration and test is planned to start in September 2020. Launch is planned in 2021. Science operations are scheduled to last at least 2 years.

SUMMARY

IXPE brings together an international collaboration to fly a dedicated x-ray polarimetry mission featuring 3 x-ray polarimeter telescopes 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 emit polarized x-rays. This paper summarized IXPE Observatory implementation along including the spacecraft and payload. The Project is deep into Phase C with both the spacecraft and payload largely mechanically integrated. Electrical testing is starting. As soon as the instrument and MMAs are delivered to Ball, payload integration will be completed. Observatory integration and test is planned to start in September 2020. IXPE will conduct world-class x-ray science using a small satellite platform starting in 2021.

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The work described here results from the combined efforts of teams at NASA MSFC, Ball Aerospace, ASI, INFN, IAPS/INAF, OHB-I, CU/LASP, Stanford University, MIT, McGill University, and Roma Tre University.

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