IXPE Mission System Concept and Development Status

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Abstract— **The goal of the Imaging X-Ray Polarimetry Explorer (IXPE) Mission, a NASA Small Explorer (SMEX), 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." IXPE, an international collaboration, will conduct X-ray imaging polarimetry for multiple categories of cosmic X-ray sources such as neutron stars, stellar-mass black holes, supernova remnants and active galactic nuclei. The Observatory uses a single science operational mode capturing the X-ray data from the targets. 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 X-ray telescopes each consisting of a polarization-sensitive, gas pixel X-ray detector, paired with its corresponding grazing incidence mirror module assembly (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-small spacecraft architecture. This paper summarizes the IXPE mission science objectives, updates the Observatory implementation concept including the payload and spacecraft elements and summarizes the mission status since last year's conference.**

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1. INTRODUCTION

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, 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 reveals 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 [1-13] 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) [14-21] 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) [3,7,22-28] and the detectors service unit (DSU) as part of the Italian Space Agency 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 [29-31]. The Science Operation Center is located at MSFC with a participation of the SSDC of ASI.

This paper summarizes the IXPE mission science objectives and mission concept of operations (CONOPS), and then describes the implementation of the Observatory including the payload and spacecraft concepts.

2. SCIENCE OBJECTIVES

IXPE directly supports NASA's first strategic objective in Astrophysics: "Discover how the universe works".[32] 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 their detailed properties including the geometry 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" [33], also recommends such measurements.

IXPE uses detailed 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 (degree and angle) and detailed imaging 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.

3. MISSION DESIGN AND CONOPS

IXPE is designed as a baseline 2-year mission with launch in Spring 2021. IXPE launches to a circular low Earth orbit (LEO) at an altitude of 570 km and an inclination of 0 degrees. The Payload uses a single science operational mode for 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, **Figure 2)** over multiple orbits (not necessarily consecutive orbits) until the observation is complete.

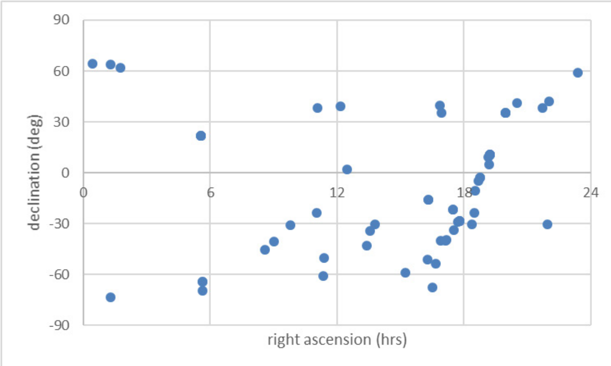

Figure 2. Distribution of Sample Science Targets on the Sky

Typically, each science target is visible over an approximate 52-day window and can be observed continuously for a minimum time of 56.7 minutes each orbit.

The IXPE Concept of Operations, summarized elsewhere [10], is shown in **Figure 3**.

4. IXPE Observatory Concept

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, **Figure 4**. A nominal IXPE target list is known in advance with targets distributed over the sky, **Figure 2.** 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. **Table 1** provides a summary of some key design updates and changes made since Mission PDR summarized in appropriate sections of this paper.

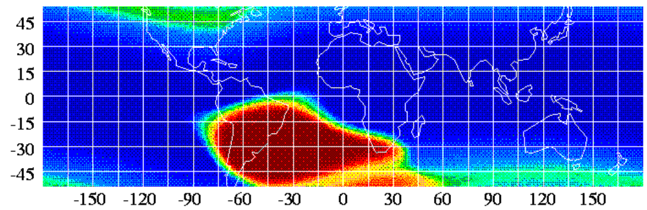

Figure 4. South Atlantic Anomaly (SAA) Distribution (Red). Near Equatorial Orbit Is Best Choice to Avoid SAA

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 5** shows the Observatory in its stowed configuration and within the Falcon 9 launch vehicle fairing compared to the Pegasus XL fairing.

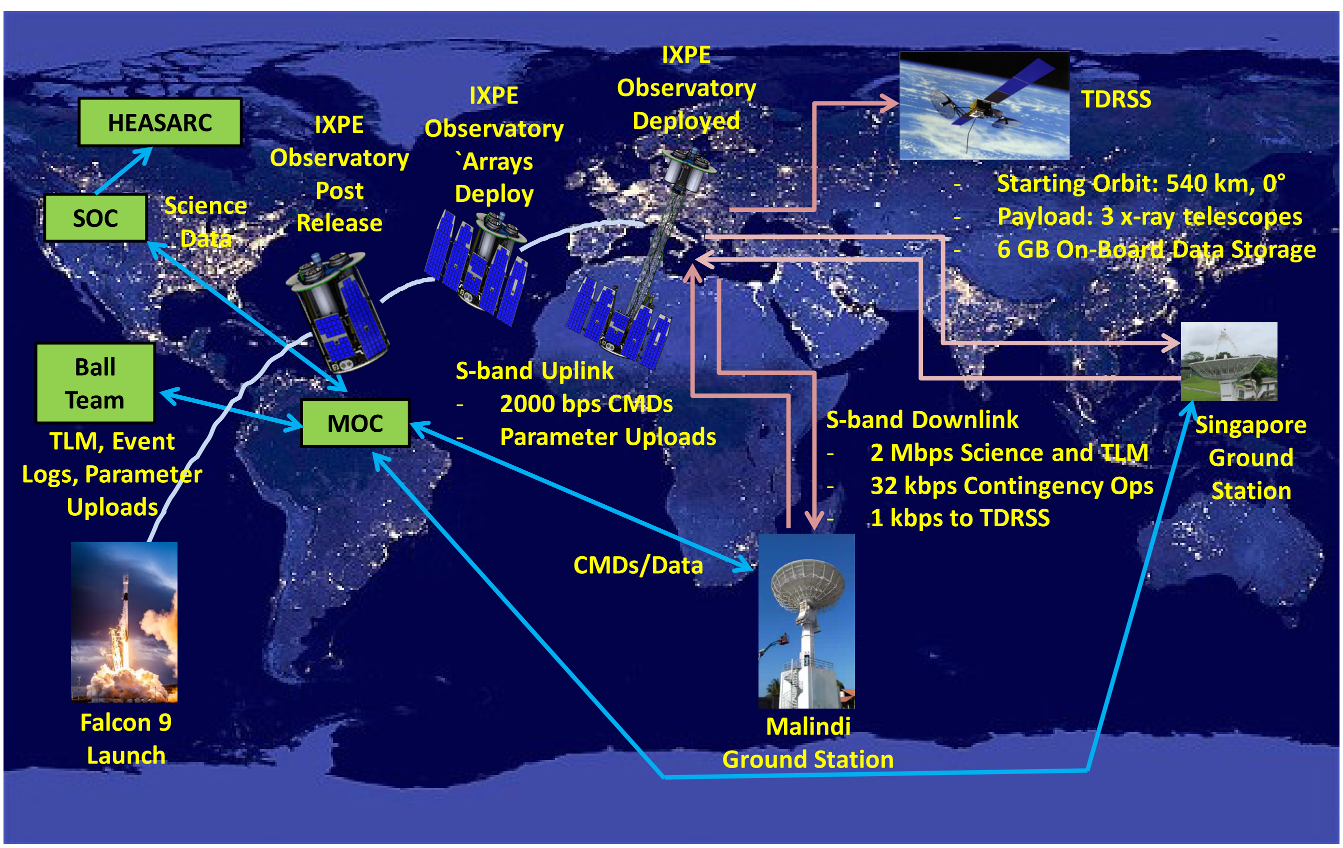

Figure 3. IXPE Concept of Operations Overview

Table 1. IXPE Key Design Updates and Changes Summary.

Design Change/Update	Result
Designed for Pegasus XL; Falcon 9 launch vehicle selected	Different launch vehicle environments (vibration, shock, acoustics); battery arming variations; launch from KSC instead of RTS; higher final orbit ≥570 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
Dithering capability added to ADCS	Support DU on-orbit calibration, within existing capabilities of ADCS with straight-forward algorithm update
Move magnetometer from SC top deck to MMSS deck	Increase separation of magnetometer from varying fields generated by torque rods
Accommodate instrument thermal dissipation	Dedicated DUs radiator tied to thermal straps, dissipates heat
Deleted metrology system	Reduce system complexity; Added home position indicators on TTR mechanism
Deployable boom risk reduction tests	Adjusted boom twist for increased stiffness; smoothed sock profile; use eddy current damper
Bipod hinged from SC top deck	Launch locks attached to brackets on straight sides of MMSS deck; more efficient load path through joints on six-sided spacecraft primary structure

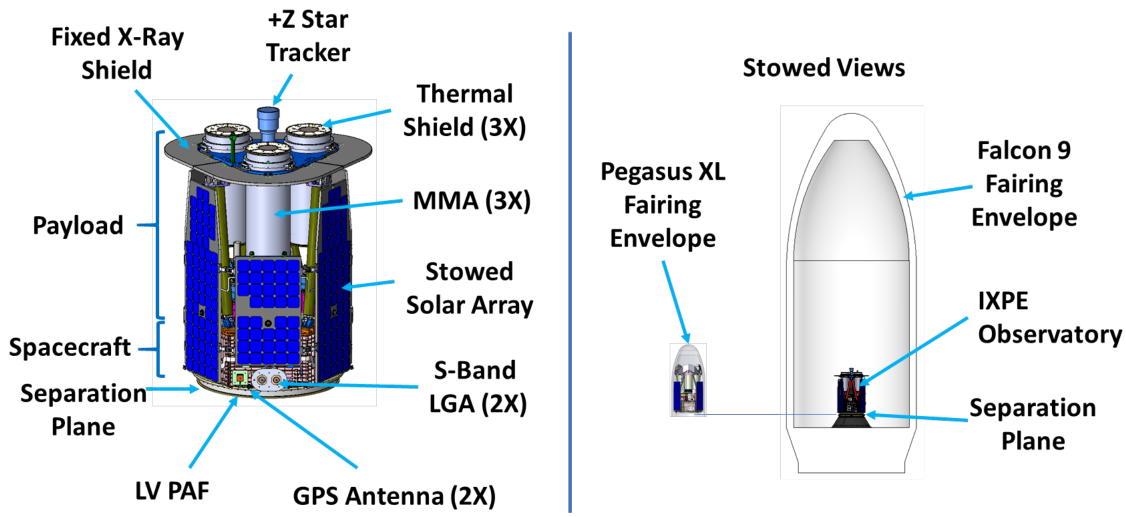

Figure 5. IXPE Observatory Stowed Configuration; in Pegasus XL and Falcon 9 Fairing Envelopes.

A view of the deployed IXPE Observatory is shown in **Figure 6.** 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 335 kg. As noted in the literature [8 – 13] the IXPE spacecraft is based on Ball's BCP-small spacecraft product line.

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 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 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 [29-31] 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 team generates IXPE data products and then archives them in High Energy Astrophysics Scientific Archive Research Center (HEASARC).

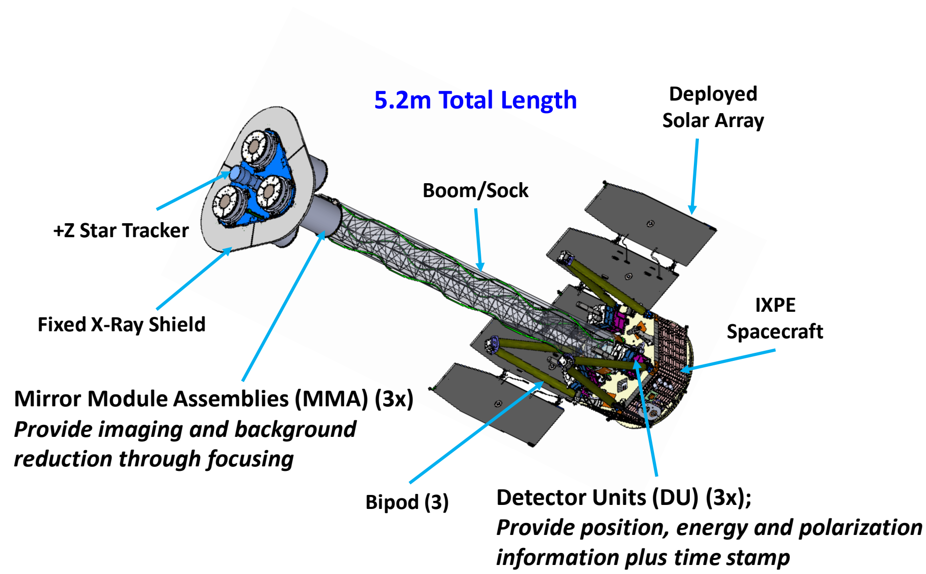

Figure 6. IXPE Observatory In Its Deployed, Science Operating Mode Configuration

5. 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 [1-13]. 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 [34]. Each DU contains its own front-end and back-end electronics, which communicate with the DSU that 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 an instrument 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 result 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 against 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 7** highlights the IXPE key payload elements.

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 use of a Falcon 9 LV enabled the replacement of deployed x-ray shields with fixed x-ray shields. The deployable boom is covered with a 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, providing system tolerance to variations in deployed geometry. The TTR includes home position indicators for precise positioning of the 3 MMAs.

MMA – MSFC provides grazing-incidence MMAs [14-21] to focus X-ray photons onto the polarization-sensitive detectors. The IXPE design achieves 209 cm^2 effective area at 2.3 keV and 243 cm^2 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 of the MMA. 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. The MMAs are calibrated at MSFC. 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, X-ray imaging detector that allows broad-band X-ray polarimetry with low net background and minimal systematic effects [22-28]. These Gas Pixel Detectors (GPD) were invented [22] and developed by the Italian members of the team and refined over the past 15 years to a high level of maturity. The GPDs

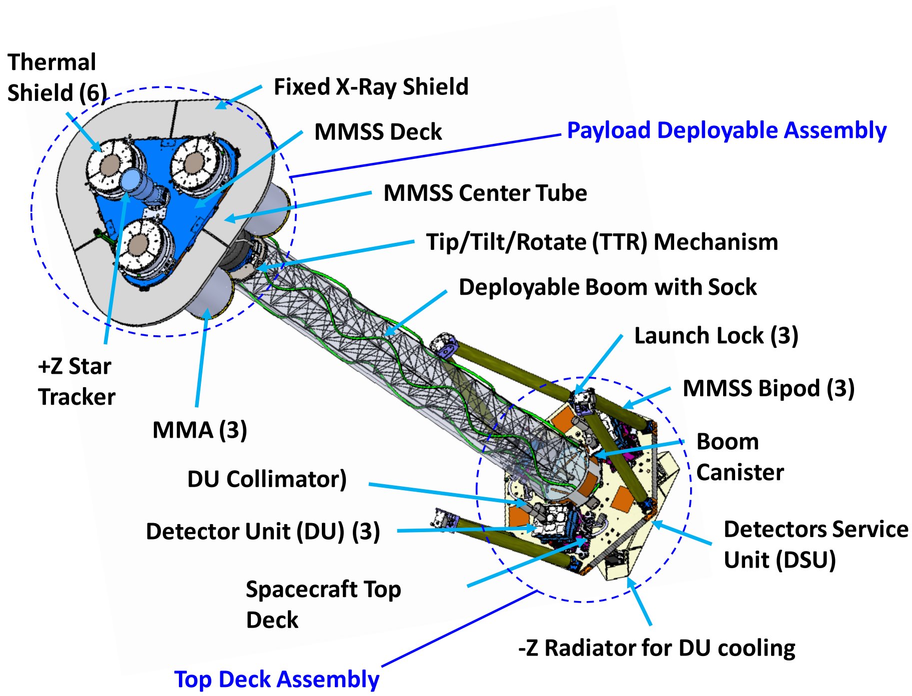

Figure 7. IXPE Oblique Top Payload View Showing Key Payload Elements

utilize the anisotropy of the emission direction of photoelectrons produced by polarized photons to measure 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. The DUs are built at INFN and then calibrated at IAPS. An FCW is included in each DU and includes polarized and un-polarized X-ray sources to check calibration on orbit. The FCW also includes an open slot, X-ray opaque slot and attenuator slot. A collimator sits on top of the DUs which, in combination with the X-ray shield around the MMAs, blocks non-imaged radiation (not passing through the X-ray optics) from entering the detectors. The DSU controls each DU, provides the needed secondary power lines to the DUs, 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 on three X-ray telescopes. Each telescope consists of an MMA and a DU. The MMAs and DUs are paired. At least one telescope will undergo full 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.

Payload Structures and Mechanisms – The three IXPE MMAs are mounted to a metallic mirror module support structure (MMSS) deck. The MMSS deck hosts the fixed X-ray shield. Three hinged bipods are attached to the spacecraft top deck to support launch loads 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.

The MMSS interfaces with the coilable, deployable boom through a Tip/Tilt/Rotation (TTR) mechanism. 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. Co-alignment of the individual MMAs with respect to each other and the star tracker, is performed during payload integration and test.

6. SPACECRAFT IMPLEMENTATION

The IXPE Observatory is based on the BCP-small spacecraft architecture described elsewhere [35-47]. The BCP-small architecture is used for the currently operating STPSat-2 [35-38], STPSat-3 [39-42], and the recently launched NASA Green Propellant Infusion Mission (GPIM) [42-47]. The

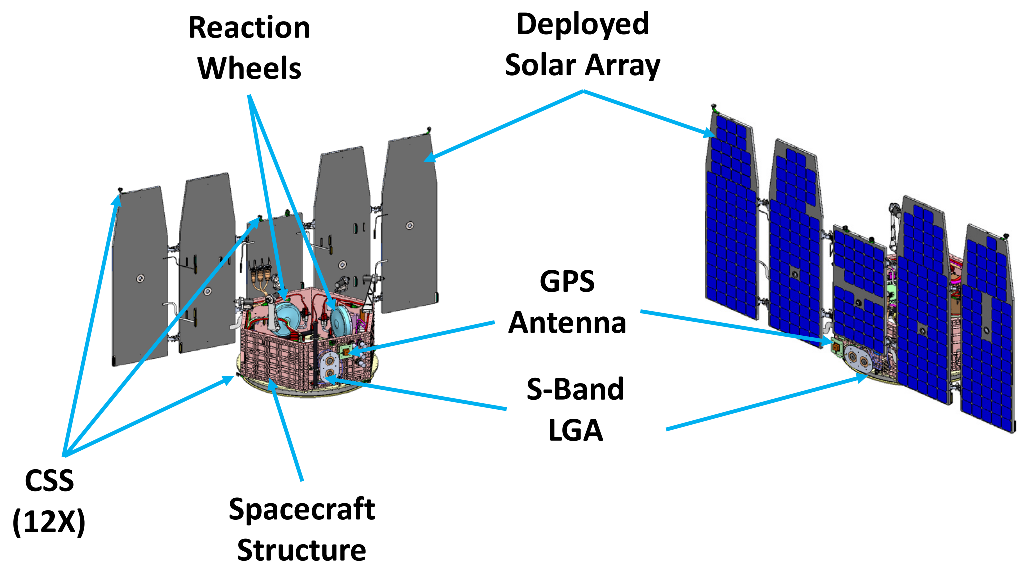

Figure 8. IXPE Spacecraft Overview. Several Spacecraft Elements Mounted On The Deployed Payload Assembly.

Table 2 IXPE Spacecraft Capabilities.

Parameter	Performance
Orbit Altitude	570 km
Orbit Inclination	~0°
Launch and Commissioning	1 month – umbilical sep to entry into science ops
Orbit Inclination	0°
Launch Mass	~335 kg
Orbit Ave Power (OAP)	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

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. The stowed solar array wraps around the spacecraft body enveloping the payload during launch and prior to deployment (Figure 5). **Table 2** highlights the capabilities of the IXPE spacecraft. **Figure 8** shows the spacecraft layout.

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. 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, 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.

Pointing Control—The mission design follows a simple observing paradigm: pointed viewing of known X-ray sources over multiple orbits until the observation is complete.

This means that the ADCS design enables the IXPE Observatory to remain pointed at the same science target for days at a time in the presence of various disturbances. [48-51] The ADCS provides a 3-axis stabilized platform controlled by reaction wheels and torque rods. Dithering capability was added and can be enabled to improve calibration of science target data. The primary attitude sensor is a star tracker with two Optical Heads (OH) and an 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, all along the Observatory's +Z-axis. The second OH is mounted to the spacecraft, aligned with the Observatory's -Z-axis. 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 torque rods with magnetometer measurements to desaturate the reaction wheels. Torque rods are sized to counter the dominant gravity gradient torque.

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 honeycomb aluminum panel spacecraft top deck. The payload envelope in the launch configuration on Falcon 9 is large, Figure 5**.** 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 is oriented towards the +Z Observatory axis and originating at the spacecraft top deck.

Power Interface—During normal mission operations, the spacecraft generates 306 W orbit average power (OAP); the payload uses ~100 W between the different payload elements including thermal control. The solar array worst case off-point is 25° [52]. The payload is provided with switched power feeds. Each power feed provides unregulated 30 ±4 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 spacecraft and 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 DUs are tied to a dedicated bottom facing radiator to reject waste heat. The MMAs are maintained to a fairly tight tolerance of 20ºC ±4ºC. 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, real-time and analog data.

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 are 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 are collected and interleaved into the real-time spacecraft downlink and are also stored in the avionics for retransmit.

7. AI&T AND ALIGNMENTS SUMMARY

Flight element integration and test (I&T) has started on the IXPE Project. All components for the spacecraft have been ordered with most delivered at this point. Flight builds for the payload components are underway. The flight boom/TTR is complete and delivered to Ball. All four flight DUs (including 1 spare) are complete while assembly of the flight MMAs is ongoing. **Figure 9** shows the top level I&T flow.

The instrument work is currently ongoing at INFN, INAF/IAPS and OHB-I in Italy. GSE/EGSE is complete. As DUs are completed they are calibrated. Calibration of the first 2 DUs is complete. The build of the flight DSU is now complete. The first completed DU is now at MSFC along with EGSE for use in detailed calibration testing with an MMA (telescope-level). End-to-end testing with the flight DSU and 3 flight DUs is ongoing.

The MMAs are being built by a dedicated team at MSFC. EM work has been completed and flight MMA assembly has started. The mirror shells are manufactured by MSFC while most of the other MMA components are fabricated under contract. GSE is complete. All flight mirror shells are complete and undergoing installation.

The MMAs and instrument are delivered to Ball for payload I&T. The instrument is installed on the spacecraft top deck

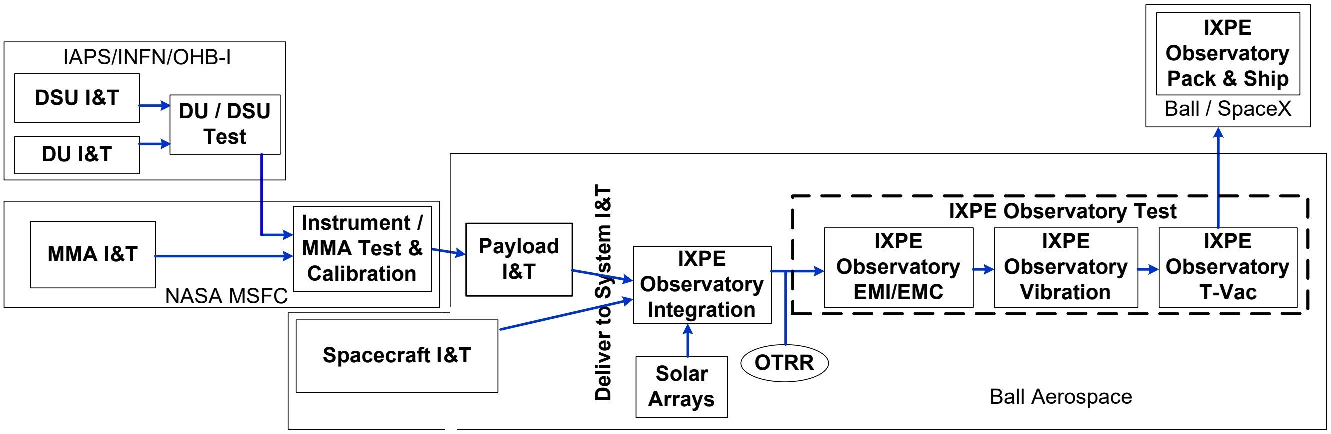

Figure 9. IXPE Observatory – IXPE Payload, Spacecraft and Observatory Integration and Test Flow

along with the boom/TTR. The MMAs are 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. The key is sizing the 'triangle' formed by the three MMAs with the 'triangle' formed by the DUs and then aligning the nodes. **Figure 10** summarizes the key elements for the alignment of the payload.

Spacecraft I&T runs in parallel to payload I&T and starts with harness, C&DH and battery installation. Flight software build number one is complete. Other subsystem elements are integrated as available.

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.

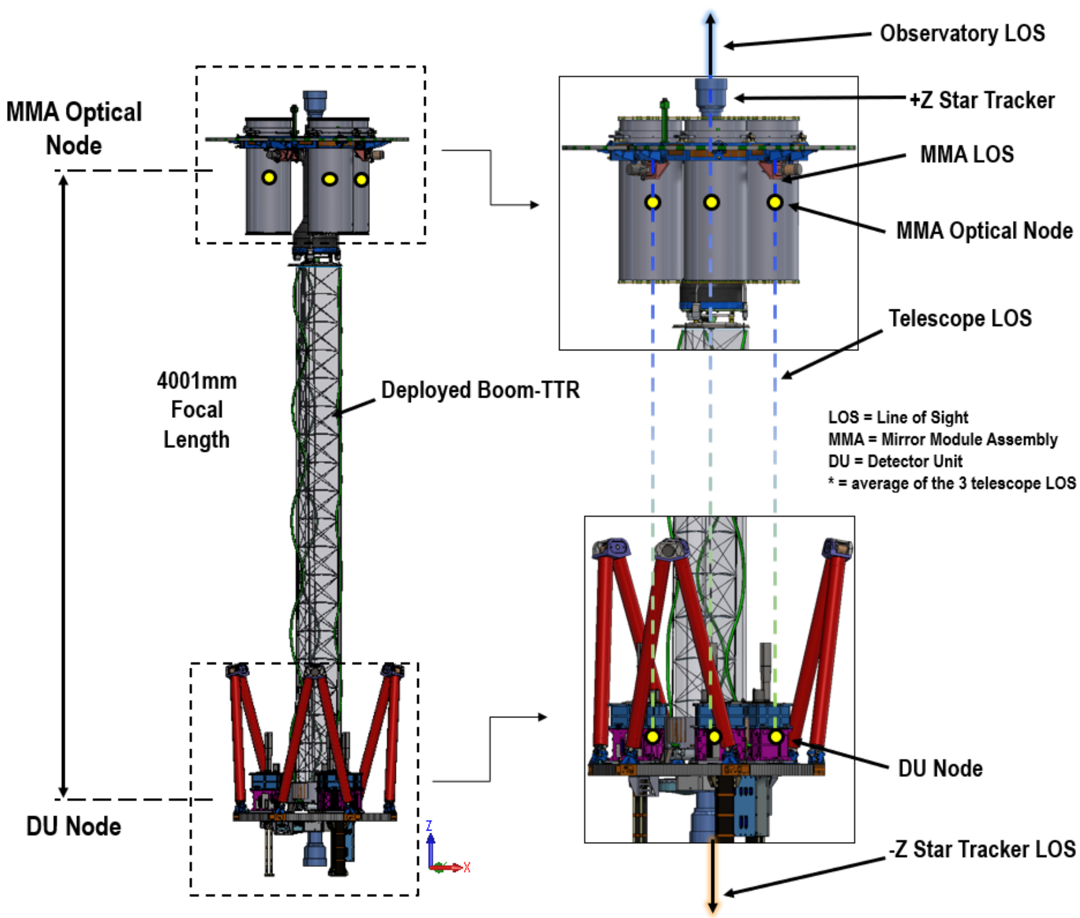

Figure 10. IXPE Payload Alignment Key Elements

8. 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 firmly into Phase C activities with Ground System PDR completed in March 2019. All major procurements are in process; most hardware deliveries have been received. The Mission CDR was completed in June 2019 and the SpaceX 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. [53] Spacecraft and Payload I&T will start in March 2020. Launch is planned in Spring 2021. Science operations are scheduled to last at least 2 years.

9. 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 the IXPE mission science objectives and Observatory implementation along with Spacecraft and Payload. The Project kicked off in February 2017. The Project is in Phase C with all major flight elements being built. Spacecraft and Payload integration is expected to start in March 2020. Launch is foreseen in Spring 2021. IXPE will conduct world-class science using a small satellite platform starting in 2021.

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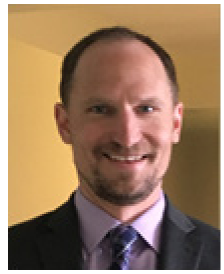

Bill Kalinowski *is a Principal Systems Engineer for Ball Aerospace. Mr. Kalinowski currently is the Ball Spacecraft Systems Engineer and spacecraft CAM on the NASA IXPE Project. He was the C&DH Lead on the Green Propellant Infusion Mission and worked in C&DH roles on JPSS-1, WorldView-3, and other missions. Before coming to Ball Aerospace, Mr. Kalinowski worked on the Orion MPCV avionics and thermal protection systems as a test and systems engineer with Stellar Solutions. Mr. Kalinowski has performed various other systems engineering and electrical design roles on the Deep Underground Science and Engineering Laboratory (DUSEL), multiple biological experiments flown aboard ISS and STS, general aviation products, and multiple commercial and government satellite systems. Mr. Kalinowski holds B.S. and M.S. degrees in Aerospace Engineering, as well as an M.E. degree in Engineering Management, all from the University of Colorado at Boulder.*

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Martin Weisskopf *is the Principle Investigator (PI) for the IXPE Mission. Dr. Martin C. Weisskopf is also Project Scientist for NASA's Chandra X-ray Observatory and Chief Scientist for X-ray Astronomy at Marshall Space Flight Center (MSFC), where he began his NASA career in 1977. Weisskopf was previously an assistant professor at Columbia University and performed many pioneering experiments in X-ray astronomy---particularly in X-ray polarimetry. He earned a bachelor's degree in physics from Oberlin College and a doctorate in physics from Brandeis University. Weisskopf is author or co-author of over 350 publications---including refereed journal articles, book articles, monographs and papers in conference proceedings and has received numerous honors---including the Rossi Prize of the High Energy Astrophysics Division of the American Astronomical Society (shared with Dr. H. Tananbaum). He is a Fellow of noth the SPIE and the American Physical Society*

Brian Ramsey *is the Deputy Principal Investigator for the IXPE Project. Dr. Ramsey is also the Payload Scientist and technical lead for the development of the X-ray mirror module assemblies. Dr Ramsey has over 40 years experience in experimental astrophysics with over 200 publications and 5 patents. His early work focused on gas-filled and solid-state X-ray detectors while recent work has focused on development of X-ray optics using electroformed-nickel-replication techniques. He has held the role of Institutional PI, Deputy PI or PI for various X-ray detector and X-ray optics projects including FOXSI, ART-XC and the HERO balloon Program. Dr. Ramsey received the NASA Exceptional Technology Achievement Medal (for X-ray optics and detectors) in 2012. He* *received a PhD in astrophysics and MS in physics from the University of Birmingham, UK. He holds a BS in physics from Brunel University, London, UK.*

Steve O'Dell *is the IXPE Chief Scientist at MSFC. Dr. Stephen L. O'Dell is an Astrophysicist at NASA's Marshall Space Flight Center (MSFC), where he serves as Deputy Project Scientist for the Chandra X-ray Observatory and as Project Scientist for the Imaging X-ray Polarimetry Explorer (IXPE). Prior to arriving at MSFC, Dr. O'Dell was a Research Physicist at the University of California in San Diego (UCSD), a Scientist at Universitäts Sternwarte Göttingen, and a Physics Professor at Virginia Tech. He earned baccalaureate and doctoral degrees in Physics from the Massachusetts Institute of Technology (MIT). His principal interests are theoretical astrophysics and x-ray optics and instrumentation.*

Allyn Tennant *is the IXPE Science Operations Center (SOC) Lead at Marshall Space Flight Center. He received his BS in Physics from the University of Texas, Austin and PhD from University of Maryland, College Park. Since 1988 he has worked at MSFC as operations scientist for AXAF (renamed to Chandra). He has been involved in the analysis of data from a variety of missions including HEAO-1, EXOSAT, RXTE, Rosat, Chandra, ART-XC and the HERO balloon program.*

Rondal Mize *is the IXPE Project System (PSE) and Chief Enginerr (CE) at MSFC. He received his BS in Agricultural Enginnering from Auburn University in 1986. During his 32 year career at NASA he has worked as mechanical design and integration engineer supporting various science payloads for the International Space Station. He also serverd as the Lead Systems Engineer and later the Chief Engineer for the Water Processing Assembly and Urine Processing Assembly for the ISS. He has served as the Chief Engineer for the Iodine Satelite CubeSat project and for the Mars Assent Vehicle...*

Michele Foster *is a Senior Systems Engineer at NASA Marshall Space Flight Center. Ms. Foster currently works on the NASA IXPE Project and the Mars Ascent Vehicle (MAV). She received a B.S. from the University of Central Florida in 1994 and a M.S. from the Florida Institute Of Technology in Melbourne, FL in 1997. During her 27-year career at NASA in project management and systems engineering, she has worked at Marshall Space Flight Center, Kennedy Space Center, and Headquarters in Washington, D.C. Her efforts have resulted in spaceflight hardware on the International Space Station and multiple CubeSats including most recently: Life Sciences Glovebox, Fast Neutron Spectrometer, Ring Sheared Drop, iodine Satellite, and NeaScout.*

Paolo Soffitta *is the IXPE Italian Principal Invesigator for the Instrument at INAF/IAPS in Rome Italy. He was detector scientist for the Stellar X-ray Polarimeter instrument and subsequently participated in the design and the developing of the Gas Pixel Detector for photoelectric polarimetery. He was also scientist of Wide Field Camera for GRBs studies on board Beppo/SAX. He helped in the design and the developing of SuperAGILE (the X-ray monitor of AGILE Gamma ray satellite) scientist. He got his PhD in Astronomy in 1997 and the Laurea degree in physics in 1990 at 'La Sapienza' in Rome. He is first author/cohautor of more than 140 refereed paper.*

Fabio Muleri *is the IXPE Italian Project Scientist for the Instrument at INAF/IAPS in Rome, Italy – he is also responsible for the IXPE Instrument Calibration. Dr. Muleri has worked on the development of the Gas Pixel Detector (GPD) since 2004. He designed, built and routinely operates anan X-ray calibration facility at INAF-IAPS to produce polarized and unpolarized beams, with an accurate knowledge of the spot size and position. This facility has been exploited to characterize the response of the GPD to polarized and unpolarized radiation and upgraded to calibrate IXPE DUs. Dr. Muleri directly participated to the design of a number of missions which included X-ray polarimeters in the payload, as well as the definition of their scientific perspectives.*

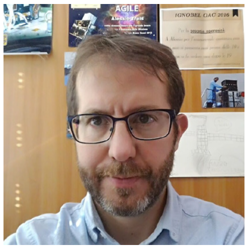
Francesco Santoli *is the I2T IXPE Instrument Lead System Engineer. He has 20 years of experience in aeronautics and aerospace. Since 2003 he is a member of the Experimental Gravitation Group of the Istituto di Astrofisica e Planetologia Spaziali (IAPS) of the Istituto Nazionale di AstroFisica (INAF) in Rome (Italy). In the past 15 years he was involved in the development of the accelerometer ISA, a scientific payload of BepiColombo ESA's mission to Mercury, and currently he is deputy PI and coordinator of ISA scientific team. He contributes to the development of the accelerometer HAA for the ESA Juice mission, and to other research projects in experimental gravitation. He holds a Master's Degree and a Ph.D. in Aerospace Engineering.*

Ettore Del Monte *is the I2T Instrument Project Office Manager, member of the IXPE Risk Management Board and member of the Project Systems Engineering Team. Dr. Del Monte received his Ph.D. in Astronomy in 2005 at the University of Roma "Tor Vergata" (Italy). He worked in the development, qualification, integration and calibration of the SuperAGILE X-ray instrument on the AGILE satellite mission, launched in 2007. After AGILE, he worked on proposals for satellite-borne X-ray instrumentation – e.g. the Large Observatory For X-ray Timing (LOFT) and the X-ray Imaging Polarimetry Explorer (XIPE) for ESA. Between 2015 and 2017 he was the coordinator of the grant COMpton Polarimeter with Avalanche Silicon readout (COMPASS), given by the Istituto Nazionale di AstroFisica (INAF) in Italy. Since 2009 he is staff member of the Istituto di Astrofisica e Planetologia Spaziali (IAPS) of the Istituto Nazionale di AstroFisica (INAF) in Rome (Italy).*

Lucca Baldini *is the IXPE Italian Co-Principal Invesigator (Co-PI) for the Instrument at INFN in Pisa, Italy and is currently an Associate Professor at Università degli Studi di Pisa. He also leads the IXPE Science Analysis and Simulation Working Group. Dr. Baldini has been a principal in the successful R&D activity on gas pixel detectors (GPD) for x-ray astronomical polarimetry—the key component of the IXPE instrument. He has provided significant contributions to the implementation of the GPD data acquisition system, event reconstruction software and the Monte Carlo simulation of the detector. Dr. Baldini has also been an active member of the Fermi Large Area Telescope (LAT) collaboration since 2002. As part of his LAT activities, he contributed to the construction of the silicon tracker, assessment and monitoring of the instrument performance and scientific data analysis. Dr. Baldini holds both MS and PhD degrees from Università degli Studi di Pisa in applied physics.*

Lucca Latronico *is the Project Office Responsible for the Instrument Detector Units at INFN in Pisa, Italy. Dr Latronico is a senior staff physicist at INFN Torino, and a member of the national INFN division on Astroparticle Physics. Latronico is a member of the Fermi Large Area Telescope (LAT) Collaboration since 2001. He served as the international LAT Analysis Coordinator, and was responsible for the calibration of the LAT Calibration Unit. As a technical member of the LAT Tracker (TKR) subsystem management team, Latronico was the contact person for INFN AIT and QA activities on the TKR.*

Michele Pinchera *is the I2T SE Mechanical/Thermal Lead for the detector units. He has over 12 years of experience in design and development of X-ray and Gamma-ray instruments. His early work focused on electric propulsion thrusters plasma diagnostics, whereas recent work focused on solid state and gas-filled X-ray detectors.He worked in calibration of the LAT instrument on the FERMI satellite mission, launched in 2008. After FERMI, he worked in proposals and studies for X-ray Observatories like the International X-ray Observatory (IXO) and the X-ray Imaging Polarimetry Explorer (XIPE). He is staff member of the Istituto Nazionale di Fisica Nucleare (INFN) in Pisa (Italy).*



Alessio Trois *is the Software; Assembly, Integration and Verification (AIV); and GSE lead for the IXPE Instrument. Mr. Trois is a member of the staff at INAF, Osservatorio Astronomico di Cagliari, Italy. He has held the role of Deputy AIV Manager on the AGILE Mission during the development phases and, at present, he holds the role of Operation Manager. After AGILE, he worked for the Sardinia Radio Telescope developing instrumentation like wide band digital spectrometers and SW for the analysis of the scientific data acquired by the antenna. Mr. Trois holds B.S. and M.S. degrees in Electronic Engineering from the University Cagliari, Italy.*

Darren Osborne *is the IXPE Flight Director at CU / LASP. Mr. Osborne has been a member of the Mission Operations and Data Systems division at LASP for over 20 years. His previous positions were as Fight Director for the ICESat and QuikSCAT missions, as well as Deputy Flight Director for the Kepler/K2 mission. Mr. Osborne holds a B.S in Aerospace Engineering from the University of Colorado at Boulder.*