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Imaging X-Ray Polarimeter Explorer Systems Engineering Approach and Implementation

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ABSTRACT

The Imaging X-ray Polarimetry Explorer (IXPE) is a NASA Small Explorer x-ray astrophysics mission being implemented by a geographically dispersed team. Each IXPE partner provides unique capabilities and experience which are utilized to design, build and launch the IXPE observatory. A rigorous and iterative systems engineering approach is essential to ensuring the successful realization of reliable and cost effective IXPE mission system. The IXPE collaboration and observatory complexity provide both unique challenges and advantages for project systems engineering. The project uses established and tailored systems engineering (SE) methods and teaming approaches to achieve the IXPE mission goals. The IXPE systems engineering team spans all partner organizations. Currently, the project is in system integration and test working through structural environmental testing – vibration testing is just starting. Systems work is now focused on requirements management and maturity assessments, requirements verification and validation via sell-off packages (SOP) and interface control document (ICD) verification while supporting environmental test planning and execution. IXPE verification, validation and characterization (V&V) starts at the component/unit level and rolls up to appropriate higher levels where V&V compliance is assured by collaborative development by the cross-organizational V&V Team. This paper provides a technical summary of the IXPE concept of operations and mission-system (payload, spacecraft, observatory, ground system, launch vehicle), overviews the IXPE systems engineering approach (communications, project reviews, requirements analysis and management, baseline design and design trade studies, interfaces definition and documentation, resource management), describes the verification, validation and characterization activities (requirements validation, models and simulations validation, systems integration and test (I&T), system validation), discusses risk and opportunities philosophy and implementation, outlines COVID 19 accommodations, itemizes some key challenges and lessons-learned followed by the path to launch and conclusions.

IXPE SCIENCE OBJECTIVES AND OVERVIEW

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, magnetars, neutron stars and pulsars. Studying the polarization of x-rays emitted from the surrounding environments of these objects can reveal their physics. The goal of the Imaging X-Ray Polarimeter Explorer (IXPE) Mission [1,2] is to expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." X-ray emission occurs from energetic processes: in-fall of matter into a neutron star or black hole, synchrotron or shock emission, or from very hot regions. Polarization of x-rays occurs if there is anisotropy in emission geometry or mag field, plasma reflections, or general relativistic effects. Polarization uniquely probes these physical anisotropies—ordered magnetic fields, aspheric matter distributions, or general relativistic coupling to black-hole spin—that are not otherwise measurable. Results from IXPE will enhance the understanding of the physical processes that produce x-rays from and near compact objects such as neutron stars and black holes. Further, IXPE will enable the exploration of the physics of the effects of gravity, energy, and electric and magnetic fields at their extreme limits

Polarimetry of cosmic x-ray sources is largely unmeasured. There are numerous studies published on polarization predictions involving emission from thermal and non-thermal processes. There have never been exhaustive polarization observations in the x-ray band. Prior x-ray missions have been limited to macroscopic imaging; spectroscopy, timing and energy measurements. X-ray polarimetry requires a large number of photons (>10E6); therefore it requires the long-term observation capability of a dedicated mission. IXPE is a unique step forward – a dedicated mission to do things never done before. Targets are observed for many hours to many days to collect enough photons. IXPE opens a new window on the x-ray universe and will perform the first extensive imaging x-ray polarization measurements of extended objects. IXPE measurements add two new dimensions to x-ray science information space: polarization degree and polarization angle.[1,2] Polarization probes the source geometry and mag field strength. In addition, x-ray emission can originate both from point and extended sources; the imaging capability of IXPE separates these sources. Imaging separates regions with different emission mechanisms.

IXPE is a low-earth-orbiting, x-ray observatory which will measure the spatial, spectral, timing, and polarization state (degree and angle) of x-rays from known astrophysical targets. IXPE will use extreme astrophysical environments of these targets as laboratories for fundamental physics addressing questions such as:

- What physical processes lead to particle acceleration & x-ray emission?
- What are the geometries of flow, emission regions and magnetic fields?
- What are the physical effects of gravitation, electric & magnetic fields at extreme limits?

The IXPE partners each provide unique capabilities and experience which are utilized to design, build, launch and operate the IXPE observatory. The Project uses established but tailored systems engineering (SE) methods and teaming approaches to achieve IXPE mission goals. This is particularly important for the dispersed team building, testing and operating IXPE. Currently, the Project is in system integration and test working through structural environmental testing. Systems work is now focused on requirements management and maturity assessments, requirements verification and validation via sell-off packages (SOP), and interface control document (ICD) verification while supporting environmental test planning and execution.

IXPE has participated in this conference before[3,4,5,6] and has described the IXPE SE processes in the past[7,8,9,10] – this paper will describe the SE philosophy as it has evolved to ensure complete inter-organizational understanding and agreement as the project moves through observatory AI&T and preparation for launch in Fall 2021.

PROJECT PARTNERS AND ROLES

IXPE is a NASA Small Explorer (SMEX) astrophysics mission and is an international collaboration lead by NASA Marshall Space Flight Center (MSFC) as the Principal Investigator (PI) institution, **Figure 1**. The mission is based on a long-term international partnership. IXPE includes 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 along with Ball Aerospace (Ball) and the University of Colorado / Laboratory for Atmospheric and Space Physics (CU/LASP). MSFC provides the grazing incidence x-ray optics and Science Operations Center (SOC) along with mission management and systems engineering. Ball is responsible for the spacecraft; payload mechanical elements; payload, spacecraft & system I&T, launch and operations. The Mission Operations Center (MOC) is located at CU/LASP. Operations are managed by Ball working with CU/LASP (similar to way Kepler/K2 was conducted). IAPS/INAF and INFN provide the unique polarization-sensitive detectors, detector units (DU) and detectors service unit (DSU) (payload computer). ASI provides the instrument and primary ground station at Malindi as international contributions to IXPE.

TECHNICAL SUMMARY

IXPE is a Class D, SMEX Mission. The IXPE Observatory is a single flight element launched to a circular LEO orbit at an altitude of 600 km and an inclination of ~0.2 degrees on a Falcon 9 launch vehicle. Launch is planned in Fall 2021. There are 2 deployments during contacts: 1) solar array deployment during the auto-initialization sequence (Space Network (SN) connectivity via TDRS) and 2) commanded boom deployment while over the Malindi ground station. Communications uses omni-directional S-band uplink/downlink. IXPE is baselined as a 2-year mission with 1-year extended mission option.

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. IXPE will be pointing and staring at known targets. Currently IXPE plans to look at 41 targets over 69

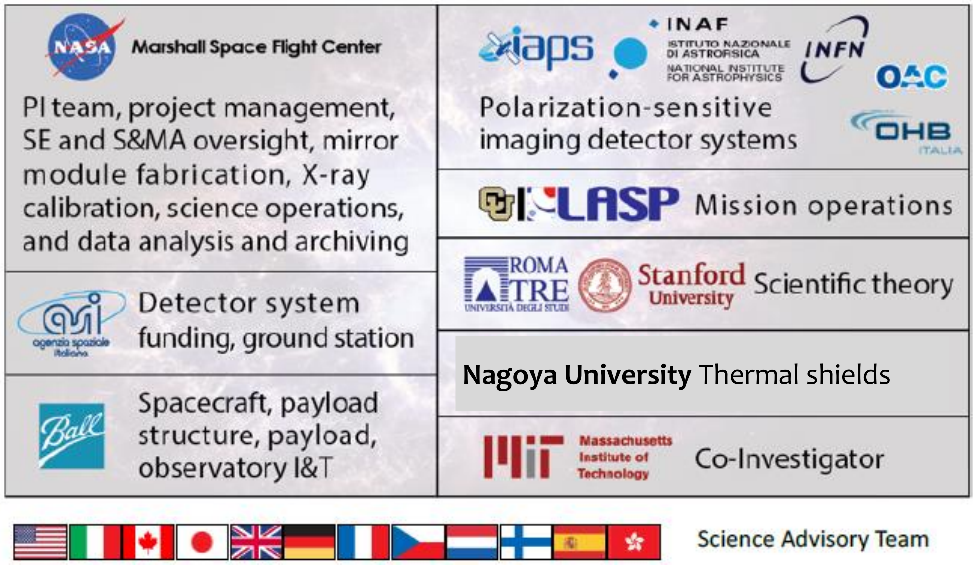

Figure 1: The IXPE Project Team is Geographically Dispersed. The Team members each bring unique capabilities to the IXPE Project.

specific observing intervals (over multiple orbits) during the first year on-orbit followed by a 12-month follow-up observing program. The ~0- degree inclination minimizes SAA pass duration. Science target observational access is through an annulus normal to sun-line of ±25° so the Observatory stays power positive. This means targets are visible ~52 days twice a year, 6 months apart. The science team generates and archives IXPE data products in HEASARC using proven algorithms.

General IXPE CONOPS Overview

The general IXPE concept of operations, shown in **Figure 2**, starts with launch from Cape Canaveral Air Force Station, Kennedy Space Center (KSC). The Falcon 9 launch vehicle injects the IXPE Observatory into the desired orbit and separates the Observatory from the upper stage. The auto-initialization sequence deploys the solar array with ground connectivity via TDRSS (downlink only). The Malindi ground station is primary with the NEN station in Singapore as a backup ground station. Spacecraft commissioning occurs over the next week. After completion of spacecraft commissioning, payload activation, commissioning and checkout occurs over a ~3 week period. These activities include commanded boom deployment while in contact with the Malindi ground station. The MOC is located at CU/LASP and the SOC at MSFC. The science data archive is located at GSFC in the HEASARC.

Payload

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, **Figure 3**. 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.[11] The MMAs are mounted in the mirror module support structure (MMSS) deck and aligned with the +Z star tracker. A tip/tilt/rotate (TTR) mechanism allows on-orbit adjustability between the deployed x-ray optics and the spacecraft top deck-mounted DUs, by moving the MMSS deck and providing system tolerance to variations in deployed geometry. Each DU contains its own electronics, which communicate via the DSU to the spacecraft. Each DU has a multi-function filter calibration wheel (FCW) assembly for in-flight calibration checks and source flux attenuation. 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.

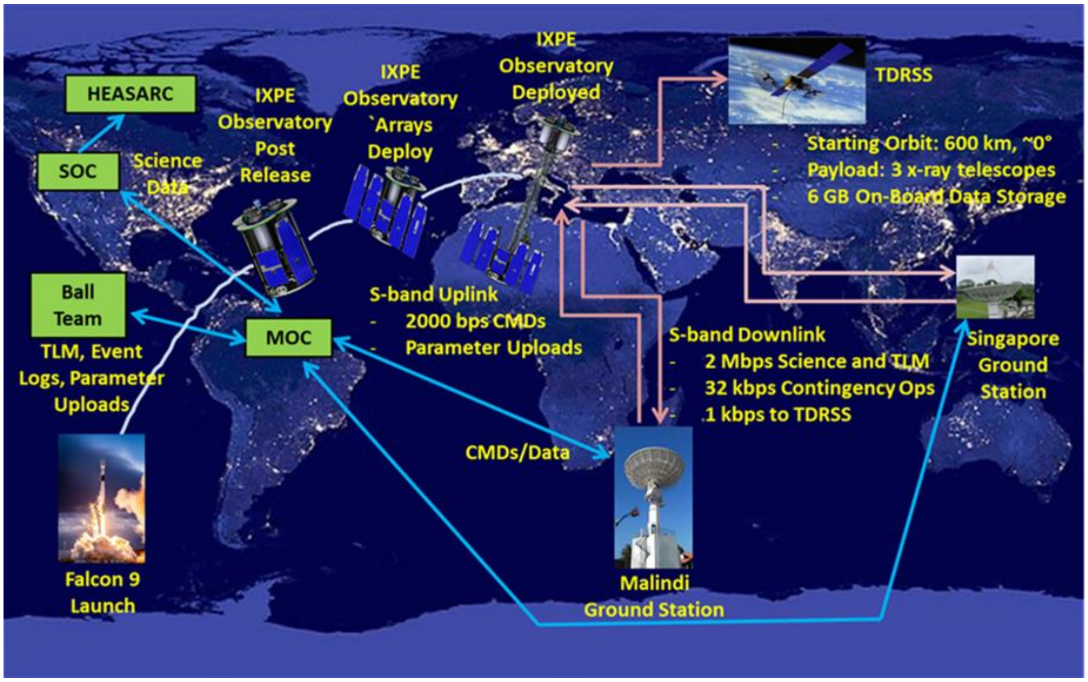

Figure 2: General IXPE Concept of Operations (CONOPS) Summary.

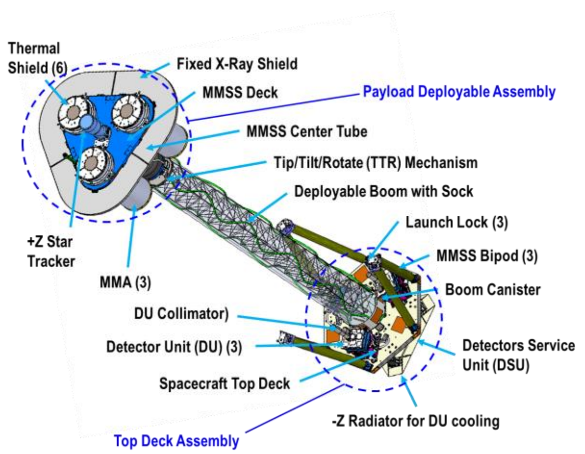

Figure 3: IXPE Oblique Top Payload View Showing Key Payload Elements.

Observatory

The IXPE Observatory consists of spacecraft and payload modules built up in parallel to form the Observatory during system integration and test. **Figure 4** shows the integrated Observatory in its stowed configuration. A view of the deployed IXPE Observatory is shown in **Figure 5**. 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 333 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 MMSS deck, 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.

Ground System

The IXPE Ground System (**Figure 6**) consists of the Mission Operations Center (MOC) at CU/LASP, the IXPE Science Operations Center (SOC) at MSFC, the Malindi ground station (with Singapore (KSAT) as a backup), and the Internet and other connections between the various elements. In addition, IXPE uses the SN-TDRS for launch and early operations support for critical event monitoring and orbit determination using differential one-way doppler (DOWD) tracking. Malindi is also used during early operations support, and during boom deployment. The Flight Dynamics

Facility (FDF) will provide improved inter-range vectors (IIRV) to the MOC and the ground stations until TLE data has converged with the FDF provided solutions. The MOC is responsible for operating the spacecraft (in collaboration with Ball) and the science payload (in collaboration with MSFC, I2T and Ball). The MOC transmits data to the SOC for processing. The SOC, with support from the ASI Space Science Data Center (SSDC), is responsible for IXPE science operations. The IXPE science team performs data processing and archiving of the data for community use through the HEASARC at GSFC.

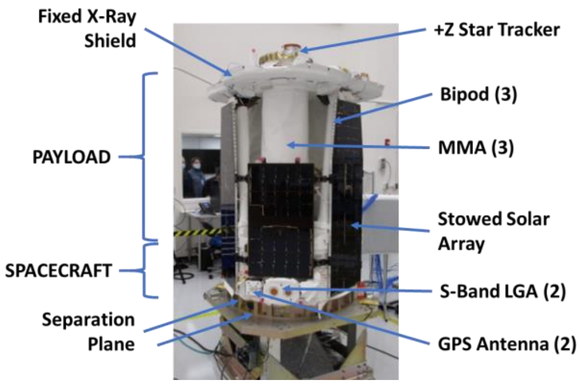

Figure 4: IXPE Observatory Stowed. Solar array wraps around the payload and spacecraft.

Launch Vehicle

As a NASA Small Explorer (SMEX), IXPE is a NASA Announcement of Opportunity (AO) selected mission. The NASA Launch Service Program (LSP) selects the launch vehicle through competitive process. At time of mission selection (Feb 2017), Pegasus XL was the only launch vehicle choice for the desired IXPE science orbit at ~0 degree inclination. Therefore, the Project Team sized the IXPE Observatory for the Pegasus XL. This met the AO requirement for a dedicated launch but with tight mass constraints. In July 2019, a dedicated Falcon 9 launch vehicle was selected to launch IXPE. Launch will occur from KSC in Florida from KSC SLC-39A in the Fall 2021.

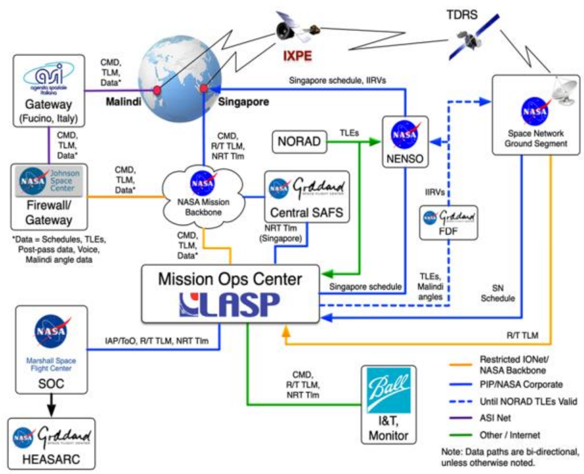

Figure 6: Ground System Network Architecture Overview and Interfaces

Figure 7 shows same-scale views of the stowed Observatory within both a Pegasus XL fairing and Falcon 9 launch vehicle fairing. Selection of Falcon 9

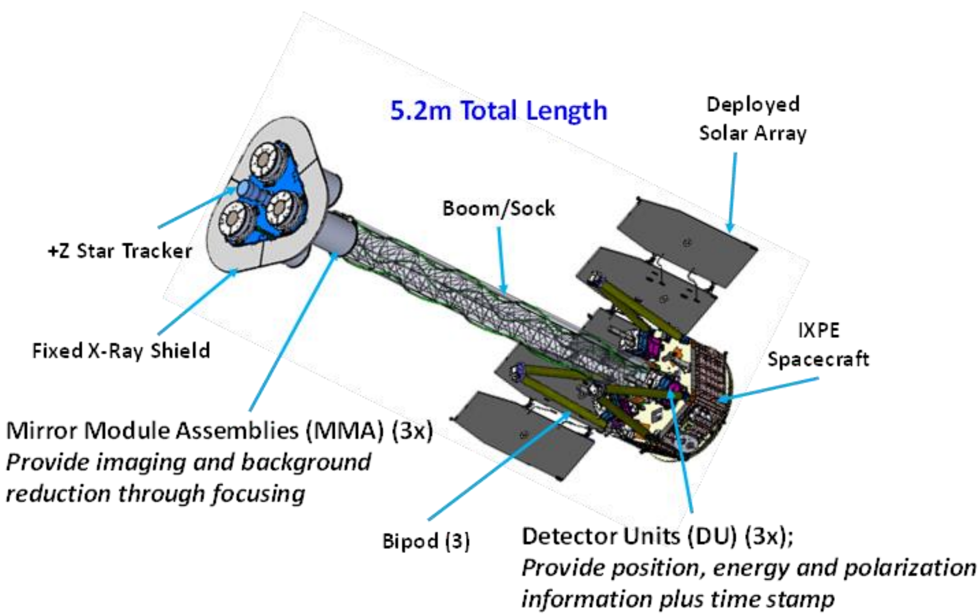

Figure 5 – IXPE Observatory in its deployed configuration.

results in a longer coast phase (~30 mins) since IXPE launches from Florida. IXPE is delivered to a higher altitude (600 km versus 540 km) due to the capabilities of Falcon 9, increasing on-orbit life for enhanced follow-on science opportunities. Launch environments (modal, vibe, shock, acoustics, thermal, EMI/EMC) vary and are factored into the IXPE architecture. A battery arming relay assembly is used for battery connectivity instead of a battery arming plug due to access issues. Finally, IXPE moved to a fixed x-ray shield eliminating the mechanisms associated with the deployable x-ray shield required for packaging within the Pegasus XL fairing. The Observatory is powered at launch. The target orbit is 600 km ±15 km at 0.20° ±0.15°. Launch mass is a maximum of 371 kg; current projections show an IXPE launch mass of ~333 kg.

IXPE SYSTEM ENGINEERING APPROACH

Systems engineering plays a substantial role in the development of IXPE.[7,8,9,10] The IXPE systems engineering approach is multi-layered and is led by MSFC with support and participation of all Project partners. The Project uses established but tailored systems engineering (SE) methods and a teaming approach to achieve IXPE mission goals – particularly important for the dispersed team building, testing and operating IXPE. Requirements management and interface control were key on IXPE as the Project started up and worked into Phase C activities. The Project is now deep in Phase D and systems work is focused on requirements maintenance, requirements verification and validation via sell-off packages (SOP), and ICD verification while supporting system I&T activies. All 'TBxs' in requirements and ICDs are closed.

The Project Systems Engineering Team (PSET) is the key IXPE SE forum. The IXPE PSET is responsible for the management of the project design space at the project level, the definition of the system requirements, management of the project's technical resources, and owns the systems cost and schedule resources of the project. Additionally, key PSET responsibilities include requirements definition/verification, analysis and management, design and interface management, technical resource management, design trade studies, technical risk identification/control, CONOPS definition and documents approval. The PSET includes members from MSFC, I2T and Ball. The systems engineering tasks are tailored and shared by the whole IXPE project team.

In addition, IXPE uses a Payload SE Technical Team meeting specifically to work payload technical details, interfaces and procedures for the payload elements focusing the instrument and MMAs. This forum includes members for MSFC, I2T and Ball. Key Payload SE Technical Team responsibilities included instrument and MMA requirements/verification analysis and management, instrument and MMA interface management, instrument and MMA technical resources assessment, technical risk identification and payload CONOPS definition.

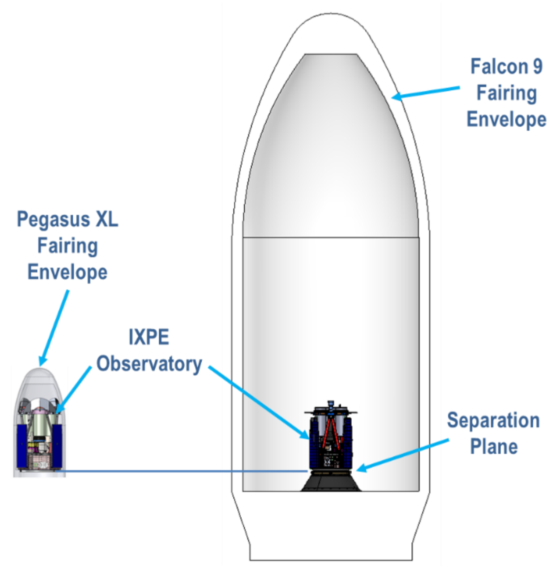

Figure 7: Stowed IXPE Observatory within Pegasus XL and Falcon 9 Fairings.

Communication

Since the IXPE project is geographically dispersed and includes international participants, clear and timely communication is fundamental to the success of the IXPE systems engineering team. The use of a shared server, common requirements database, memoranda, e-mail, weekly telecons, and weekly staff meetings are also crucial to the SE effort. SE leverages all levels of written and verbal communications, as appropriate, to maintain cognizance of the evolution of all system requirements, interface issues, possible trade studies, and sources of project risk. Informal, frequent communications between all IXPE team members is also a hallmark of Project execution including regular face-to-face meetings (pre-pandemic).

Project Reviews

IXPE is assessed technically at several reviews across its life cycle per the IXPE Project Review Plan. In addition, the IXPE Project holds many internal reviews to track and assess technical and programmatic progress. All project reviews, including reviews of technical and programmatic status are included in the project Integrated Master Schedule (IMS). Major Project technical reviews are convened by systems engineering. Key major Project reviews include: Systems Requirements Review (SRR), Instrument Preliminary Design Review (IPDR) Spacecraft PDR, Payload PDR, Ground Segment PDR, Project PDR, Key Decision Point C (KDP-C), Project Critical Design Review (CDR), Ground Segment CDR, KDP-D, Spacecraft Integration Readiness Review (SIRR), Payload IRR, Observatory IRR, Mission Systems Integration Review (MSIR), Payload Test Readiness Review (PTRR), Observatory Pre-Environmental Test Review (OPER), Mission Readiness Review (MRR), Pack and Ship Review (PSR), Operational Readiness Review (ORR), Launch Readiness Review (LRR).

A SMEX-assigned Standing Review Board (SRB) governs the following IXPE reviews: SRR, PDR, CDR, MSIR and LRR. The IXPE PSE is responsible for coordinating the reviews with the SRB. The PSET will support each of these reviews by completing and providing the products and appropriate review materials. Each review will be used to assess progress vs. project plans; assess risk, reserve, and resource margin status, and report any items of concern, whether, cost, technical, or schedule related Critical milestone reviews include a description of the disposition of all requests for action (RFA) form.

In conjunction with these project reviews, the IXPE partners will conduct appropriate reviews at the subsystem and component levels.

Requirements analysis and management

The IXPE Team has been using an iterative, science needs-driven requirements flowdown process, **Figure 8**. It starts with science needs and requirements based on the science target types and distribution on the sky. Models and hardware specifications interact with one another by passing inputs and spec values to determine how best to address the science needs on a design to cost mission. Observatory performance is assessed as requirements are refined and hardware specs are traded. A concept of operations (CONOPS) is developed to enable the science data collection for all targets within the required orbital lifetime with margin. This CONOPS is used to derive requirements key to meeting mission objectives. Iterations, often involving trades and risk assessments, occur to improve budgets and performance. Requirements analysis and flowdown is an iterative process.

The IXPE Project documents requirements as shall statements down to level 3. These requirements are managed through the systems engineering team, captured in the DOORS requirements management tool, and approved by the PI (or the PI's designee) and the PSE. DOORS provides configuration control and is used to implement the requirements traceability and verification matrices. The verification matrices will be utilized to confirm that all the project requirements have been met and that the project is ready for launch and operations. Additionally, program requirements such as cost limits, needed reserves, and launch dates for the Small Explorer (SMEX) projects are defined by the NASA Science Mission Directorate (SMD). These requirements along with the mission level performance requirements that were defined in the proposal by the PI form the basis of the Project level 1 requirements.

The IXPE project derives the project system requirements (level 2) from these program requirements (level 1). The IXPE level 2 project requirements have been decomposed into three components: Observatory (OBS), Ground Segment (GS) and Launch Vehicle (LV). Each system and element has developed system requirements (level 3) from the science and project system requirements (level 2). These requirements have gone through the PSET approval process. Ball, MSFC and I2T have decomposed Level 3 requirements to Level 4 and 5 requirements to support hardware/software build.

The requirements hierarchy is shown in the **Figure 9** including how the hierarchy has matured with the Project. The original spec tree was overcome by international partner needs in that the Project created requirements document for ASI to flow to the Instrument team, the Mission Unique Requirements Document (MURD). The MURD was developed to flow instrument-related Level 1, 2, & 3 requirements to Instrument Spec. Special coordination between Ball and I2T was implemented to ensure the DOORS databases at both organizations remained consistent. Level 3 payload specs were consolidated based on design maturation since the metrology system was eliminated for simplification, the payload electronics functions distributed into SC IAU and the science calibration spec moved to I&T processes.

Baseline Design and Design Trade Studies

The IXPE Project baseline design is documented using the System Engineering Data Book (SEDB) construct.[16] The development of a mission system concept (flight system, launch vehicle, ground system) is typically an iterative process requiring a balance of technical, cost, risk, and schedule considerations. With the full understanding of the requirements and the programmatic context, the systems team performs flight systems definition work including conceptualization, best-value trades, cost performance analysis, requirements definition and assessment, interface establishment, technical performance metrics (TPM) definition and tracking, and program/project

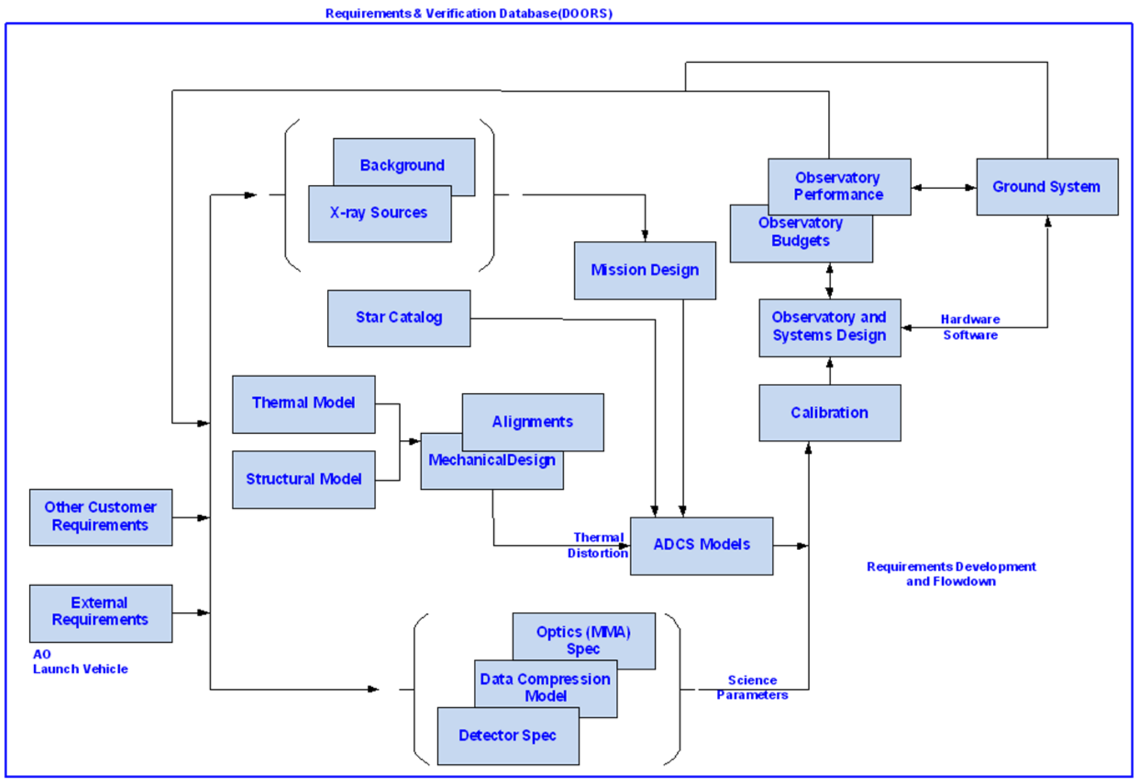

Figure 8: IXPE Requirements Definition Flow.

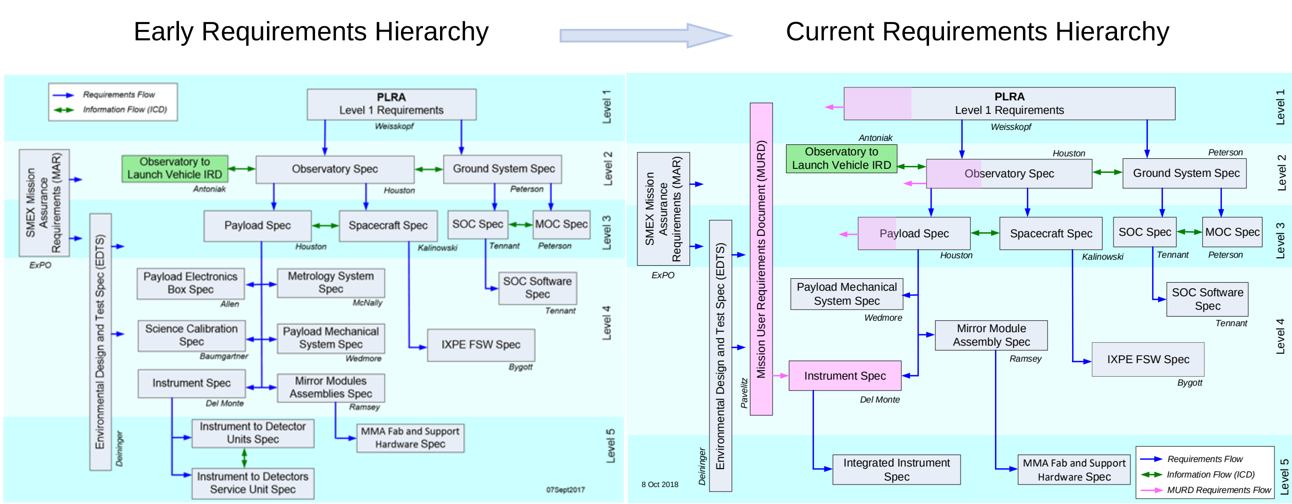

Figure 9: IXPE Requirements Hierarchy Evolution.

communication, coordination, and reporting. A synthesis of this information is used to report the program/project mission system baseline at any time during the project development cycle.

A program/project baseline is a reference configuration from which to identify and to control change. The set of documents that report a specific product technical baseline at Ball are referred to as the Systems Engineering Data Book (SEDB). The SEDB is a set of living documents kept in electronic format that matures as the program/project progresses towards final delivery. Due to the way various aspects of a mission system mature, not all sections of the SEDB are expected to be at the same level of maturity at the same time. In early baselines, frequent or significant changes are the norm; changes in later baselines occur less frequently and require compelling justification and documentation. The SEDB has formed the technical basis for program/project reviews (SRR, SDR, PDR, and CDR along with table-top and peer reviews) for all of the various elements of the flight system. More importantly, the SEDB also facilitates cross-discipline/cross-subsystem communication and coordination is has been used as the basis for peer reviews. The SEDB does not replace other program/project documentation such as technical reports and specifications that contain more detailed data; it instead summarizes this information within its various sections.

Establishment and maintenance of a current program/project technical baseline is the responsibility of the systems engineering team. Responsible Engineers (RE) keep track of the technical baseline for subsystems and components.

The Chief Engineer (CE) maintains a list of all issues and design trade studies currently open on the project. There are dedicated working group meetings to work to closure open design issues. All trade studies are documented in reports and SEDB. The CE is responsible for tracking all open issues and trade studies and provides status (number open, and closure rate over time) at the monthly management reviews. Each issue or trade study will be reviewed at the PSET. PSET meetings will be used to discuss the status of open design issues, and trade studies.

Interfaces Definition and Documentation

IXPE is a small project with the partner interfaces of a big project. IXPE involves of 2 national space agencies (NASA and ASI) and multiple national agencies from Italy (INAF, INFN) and the USA (NASA HQ SMD, NASA GSFC (SMEX Program Office), NASA MSFC (IXPE Project Office), and NASA LSP). There are multiple international partners and subcontractors including Ball Aerospace, OHB-Italia, SpaceX and subcontractors working with each organization. IXPE uses multiple Ground Systems with the ASI-contributed Malindi station as the primary ground station, the TDRSS Space Network (SN) used for early operations and contingencies and the NEN/KSAT station in Singapore as the backup ground station. Several university laboratories have played key roles in the development of the IXPE mission system including LASP at the University of Colorado and Nagoya University in Japan. There are many interface control documents (ICDs) tying the work of all these organizations together.

Interface control and documentation is a key function for systems engineering on IXPE. In general, the partner leading the subsystem is the owner of the ICD. Interfaces were developed through a collaborative process involving all stake holders. ICDs define the external interfaces between the Observatory and launch vehicle, Malindi ground station, NEN Singapore station, TDRSS SN, and the MOC (for testing) and SOC, **Figure 10**. ICDs govern MOC to Malindi ground station, NEN Singapore station, TDRSS SN assets. There is a dedicated ICD between the MOC and SOC.

ICDs are defined between all major Observatory elements provided from one partner to another, **Figure 11**. There is a dedicated ICD between then MMAs and the mirror module support structure (MMSS) deck. There is also a detailed ICD between the spacecraft and instrument. For example, instrument I/F accommodation was accomplished with a collaboration between I2T, MSFC and Ball. The interface definition team held multiple face-to-face TIMs and Project meetings. The focus was documenting both sides of the instrument interface from mechanical, thermal, electrical and software perspectives. The interface team worked to drive closure of the Instrument-to-Spacecraft ICD using a regular weekly forum for discussion and closure of technical issues. Further, a spacecraft simulator was provided to I2T to ring out electrical and data interfaces while providing confidence the interface works.

Resource Management

The IXPE system engineering team is responsible for tracking and reporting on the technical resources throughout the project lifecycle. The emphasis on IXPE has been to design in large technical performance margins (TPMs) as a way of dealing with implementation risk. These TPMs are given a fixed allocation at the start of the project phase and margins are tracked through design and implementation. The CE identifies mass, power, and other critical IXPE resource margins for the payload, the spacecraft, and the overall mission. The CE is responsible for collecting and reporting the observatory, spacecraft and instrument level information. The TPMs are reported at the Monthly Management Reviews and key project milestone reviews.

The IXPE team will continuously analyze and track TPMs against their allocation to monitor trends and uncover potential risks. Specific IXPE TPM tracking with monthly reporting has included requirements counts and changes, mass, power, line-of-sight (LOS) pointing accuracy, LOS co-alignment accuracy, angular resolution, uplink and downlink margins, axial and radial center-of-mass in launch configuration, CPU utilization, data storage and mission data volume. For example, **Figure 12** shows mass margin tracking for the IXPE Project to date; current launch margin for the fully integrated observatory s 12%.

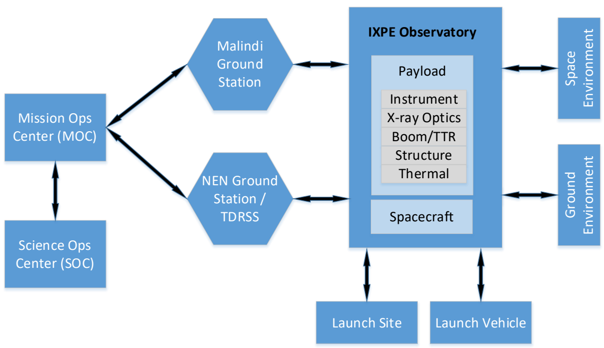

Figure 10: IXPE External Flight Interfaces.

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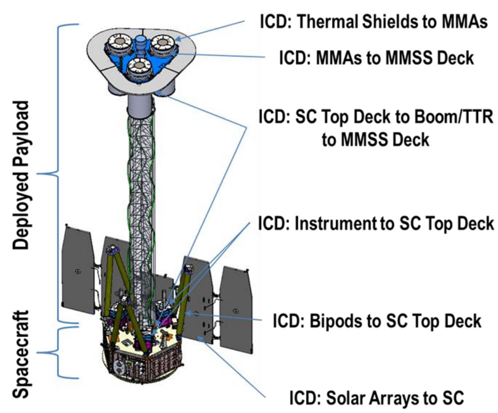

Figure 11: IXPE Internal Observatory interfaces.

VERIFICATION AND VALIDATION

Systematic and comprehensive verification, validation and characterization (V&V) is critical to achieve mission success.[17,18,19] V&V is shared across the Project team and is an iterative process that spans the duration of the Project build through launch and beyond to reach closure. A rigorous and iterative V&V process is essential to ensuring the successful realization of reliable and cost effective IXPE Mission System. The IXPE collaboration is being implemented by a geographically dispersed team (see 'Project Partners and Roles' above) which when coupled to the Observatory's complexity provides both unique challenges and advantages for Project V&V. V&V compliance is assured by collaborative development by the V&V Team which spans all project organizations. The IXPE V&V process is part of the IXPE systems engineering process and provides a framework, with appropriate confidence, to show that all needs and expectations are met by the as-built system. Proof is in the form of traceable detailed evidence of compliance at every level rolling up to and including the overall system and architecture levels.

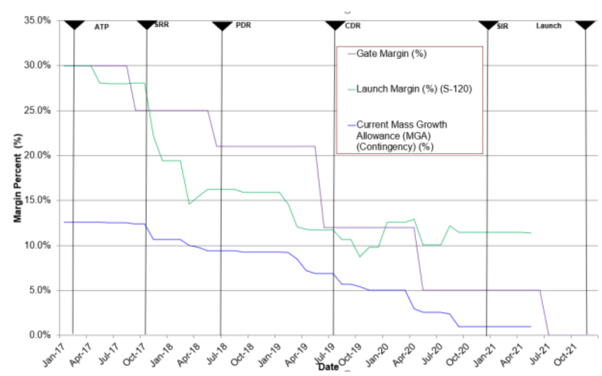

Figure 12: IXPE Internal Observatory interfaces.

The project level V&V Plan defines the approach for performing verification and validation of the project products and defines the methodology to be used in the verification/validation tests, analyses, inspections, and demonstrations. As requirements are defined, verification methods, levels, phases, and success criteria are identified and tracked in a Requirements Verification Matrix (RVM). The IXPE V&V process starts at the component/unit level, rolls up through appropriate higher levels to the Observatory and mission-system levels. I2T is responsible for V&V of the instrument (3 DUs, DSU, interconnecting cabling). MSFC is responsible for V&V of the MMAs and the telescopes. These activities support the roll up of V&V from the lower levels up to higher levels. Ball is responsible for the V&V efforts rolling up through the overall payload and spacecraft to the Observatory on behalf of MSFC.

Verification and validation activities are done to provide objective evidence that IXPE meets its design requirements, stakeholders' needs and is ready for its mission. Overall, IXPE's V&V philosophy is to integrate and verify subsystems before system integration and flight considering cost, schedule, and technical impacts with associated risks. IXPE is being designed with a proto-flight verification approach such that test hardware in most cases is also the flight hardware. There are engineering units for the MMAs and the instrument which undergo qualification-level verification testing. The integrated IXPE system will be tested to acceptance-levels.

The V&V activities on the IXPE Project consist of requirements validation, development and validation of models and algorithms, verification of each system-level requirement, and characterization of key observatory, spacecraft and payload performance parameters. Models and simulations used for IXPE development and operations include elements from each of the partners. Models and simulations validation involves reasonableness, piece-wise, peer, and/or independent assessments. System validation is largely achieved as part of Observatory I&T.

V&V at the lowest level possible will be used and rolled up to the next higher level of the IXPE architecture until the entire system is verified and validated. As design requirements were decomposed from system requirements, the verification method(s) for each requirement was identified. This ensured IXPE only levied verifiable design requirements.

While verification by test is the preferred method, it is not always feasible considering available resources. When testing is not feasible, IXPE will verify by inspection, analysis, and/or demonstration at the lowest level. In some cases, a combination of inspection or demonstration along with analysis is planned. Inspection is a visual examination verifying dimensions, specific markings, or dimensions. Demonstration is used when observing a functional operation but is different than testing since elaborate instrumentation or special test equipment is not needed. Demonstration is typically a based on pass/fail criteria. Higher level requirements V&V is done as applicable lower level requirements are shown to have been verified through the roll up process. IXPE systems engineering team is responsible for planning the V&V activities for requirements in Levels 1-3. Partners responsible for developing and implementing V&V plans at the levels 3 and 4. The PSE and LSE are responsible for tracking all unresolved V&V issues.

As shown in **Figure 13**, V&V flow starts with the identification of the mission needs as identified by science team. The process flow incorporates iterative requirements analysis, requirements flowdown and Requirements Verification Matrix (RVM) development/maturation. It ensures mission CONOPS is used to support requirements definition. Test planning (performance & characterization), modeling, simulation and analyses are integrated into V&V process. Risk management is integrated into the V&V process flow to ensure activities balance. Mitigation steps are tied to risks which are fed into the V&V process to help define focused V&V activities for risks mitigation when within mission constraints (Project technical, cost, schedule, risk tolerance balance). There are typically several iteration loops as new information becomes available; design matures and testing and analyses are completed. This process results in a verified, validated, and characterized system.

Submittal of V&V closures are done in sell-off packages (SOP) prepared by Ball. Review and closure of the SOP is submitted to the verification specification owner(s), **Figure 14**, and are planned to enable SOP closure as the Project progresses. Launch Vehicle (LV) ICD requirements are managed by LSP and SpaceX.

Project level requirements identified as being verified by test or demonstration are documented in an overall project test plan. This plan will include the detailed test flow and procedures and ensure NASA quality assurance is included as necessary when system tests are done at MSFC. The requirements themselves are listed in the pertinent test plan. Appropriate verifications will be maintained and identified between the engineering test unit and the flight unit.

IXPE Requirements Validation Process

Requirements validation, **Figure 15**, demonstrates that the requirements will satisfy the mission science objectives prior to the system being built – It's the process of confirming the completeness and correctness of the requirements. Requirements validation is integral to the requirements synthesis effort and answers the question: "Are the system design requirements correctly defined and mean what we intended?" Requirements validation demonstrates that the requirements will satisfy the mission science objectives prior to the system being built. It's the process of confirming the completeness and correctness of the requirements. Requirements validation is integral to the requirements synthesis effort and answers the question: "Are the system design requirements correctly defined and mean what we intended?".

Each requirement, at all levels in the specification tree is validated in view of the Project risk posture. An overall fault-tree analysis is conducted looking at mission hardware and software elements in light of the largely single string nature of the IXPE mission implementation. Selected worst-case and parts-stress analyses are conducted based on critically and risk. Margins testing is conducted with prototype and EM hardware where available. "Soft-spots" drive redundancy assessment, fault protection definition and additional testing at payload, spacecraft and / or Observatory level. For requirement validation there are five major elements:

- Correctness – does the requirement achieve the driving need?

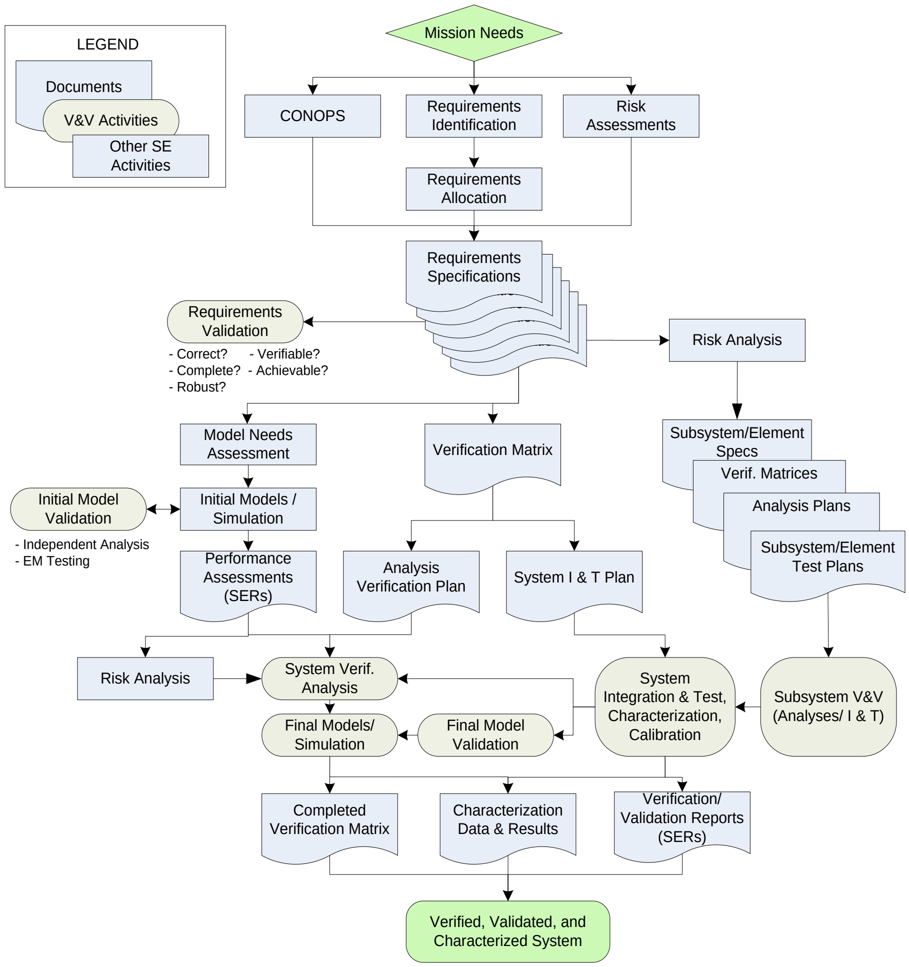

Figure 13: IXPE Mission System V&V Process Flow.

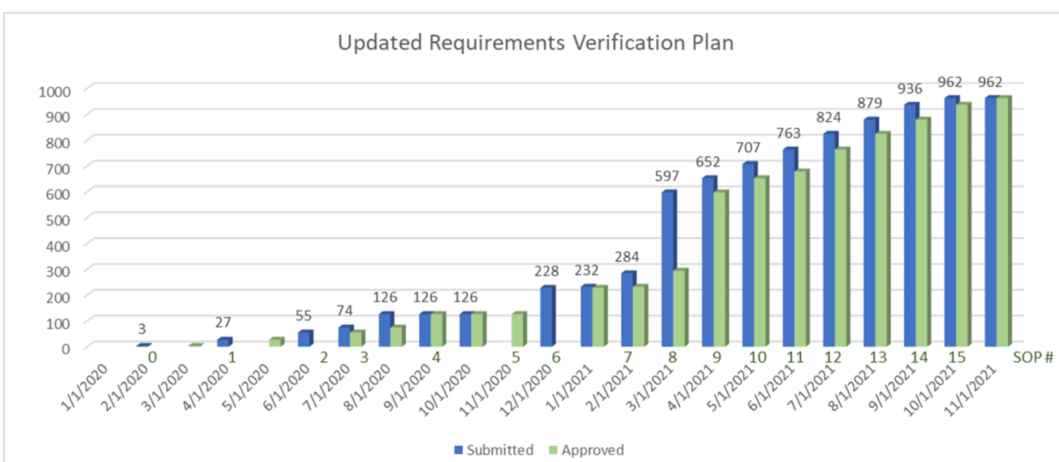

Figure 14: Requirements Sell-Off-Package (SOP) Plan.

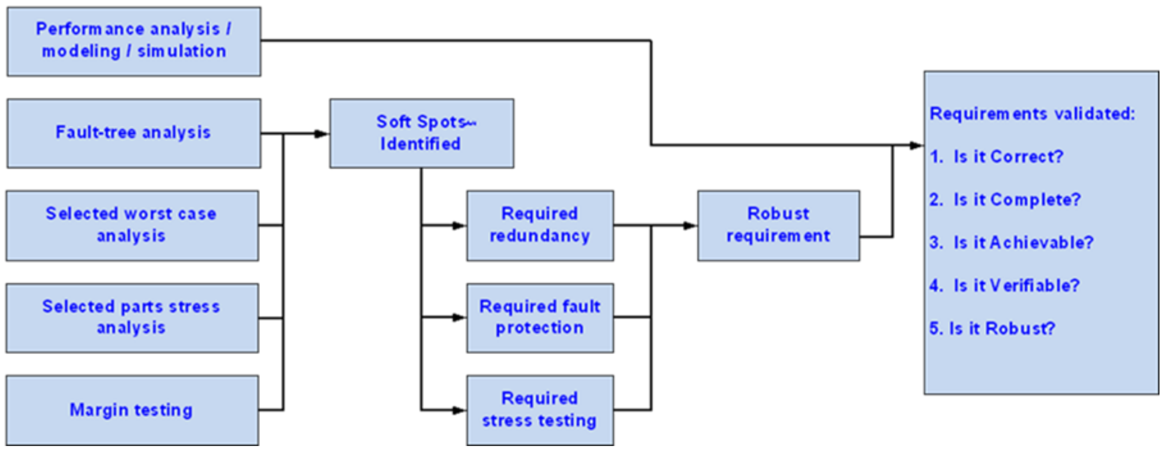

Figure 15: Requirements Validation on IXPE.

- Completeness – is the requirement unambiguous, stand-alone, concise, and non-conflicting?
- Achievable – can the requirement be met within IXPE's scope?
- Verifiable – can the requirement be verified on the as-built system?
- Robust – does the requirement push against any firm limits?

Requirements validation relies on performance budgets and margins. IXPE has had minimal ripple in Level 1 requirements since the completion of the Phase A activities (Concept Study Report (CSR)).

IXPE Models/Simulation Validation

Early in the program, a 'model needs assessment' is performed where areas that need analysis for verification to satisfy the V&V needs are determined. Models and simulations that are mission-critical are identified. Preliminary analysis models are identified and matched against the requirements to determine if the identified models are sufficient. Models and simulations that are used to span gaps in the test program, are treated as mission-critical and are formally validated during element, subsystem and/or system level testing. Model validation spans the project life-cycle (incremental refinement). Initial validation of the models is informal and performed by 1) independent analysis, and 2) comparison to EM test data. Examples of independent analyses include:

- Face Validation: subject-matter experts—do model results "seem believable?"
- Peer Review: of model equations and code for correctness.
- Functional Decomposition and Test: piece-wise testing of individual code modules (inject test inputs and examine outputs).
- Empirical Validation: compare model results with those from a test of the real system or some analog.

Analysis and models are used to check the design against the requirements at each stage of the project cycle. Analysis is also applied to ensure that tests have adequate sensitivity to measure the design parameter. Each analysis is documented in a System Engineering Report (SER). Where appropriate, models are validated by test to enable realistic on-orbit predictions of behavior (observatory thermal model (thermal vacuum testing), structural model (modal, vibration, shock & acoustics testing)) and pointing (ADCS sensor and actuator capabilities). Model validation demonstrates that the models and simulations used to support requirements validation, system validation, and verification are correct.

Systems Integration and Test

The system integration and test program (payload, spacecraft and Observatory) is developed to sufficiently test workmanship and operational aspects of the IXPE design. Much of system validation is done via testing. **Figure 16** shows the overall flow of the IXPE Integration and Test activities. System validation can include limits-testing which will be prioritized and implemented based on available project resources balanced with risk assessments.

IXPE starts the V&V process at the lowest level possible with analyses and conservative testing. The component/unit level test requirements are documented. The I&T steps contain schedule margin and slack to ensure time to do the work correctly the first time. Interfaces are documented early and interface and harness mating tests are conducted as soon as is practical. System level EMI/EMC testing is done at the observatory level. GSE checkout, interfaces and

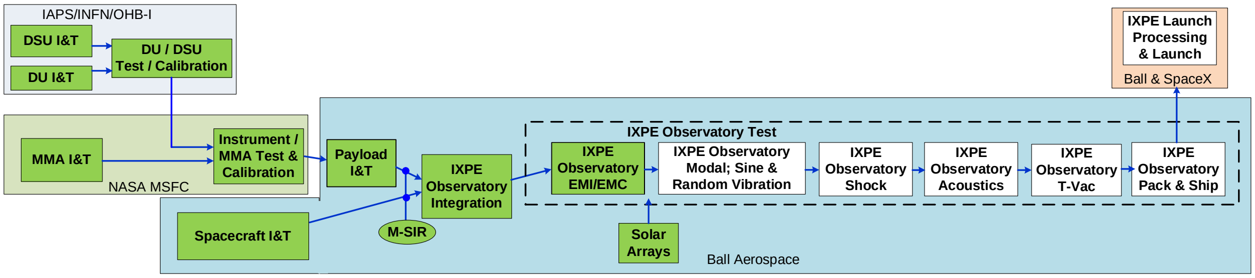

Figure 16: IXPE Top-Level Integration & Test Flow.

verification is conducted well before need on the test floor. Test planning started early (Phase A) and has continued through the design and build process with increasing detail.

IXPE uses a heritage, disciplined anomaly tracking and resolution process at Ball covering vendors, subcontractors, factory floor, launch site and on-orbit anomalies. This process convenes Failure Review Boards (FRB) and/or Material Review Boards (MRB), as needed, to ensure root cause is determined and corrective actions include all effected hardware, software documentation and involved organizations.

In some cases, the parameter of interest is not directly tested, but may be derived from the test data through some mathematical computation. Analysis converts test data to verifiable parameters and verifies non-testable requirements. Often, it is not possible to fully duplicate all on orbit conditions on the ground which is documented in IXPE Test-Like-You-Fly (TLYF) exceptions. Data derived from integration and test are used to validate the models. Once validated for ground conditions, the models are then used to “extrapolate” performance for on-orbit conditions.

The IXPE Project has identified multiple levels of assembly at which verification testing may be performed:

- System: System-level verification implies the integration or dependency of multiple subsystems that must be evaluated as a whole before the applicable requirement can be verified. A system-level test or inspection usually occurs in the mature stages of the integration cycle. System-level testing includes spacecraft-, payload- and Observatory-level testing as well as all end-to-end compatibility tests.
- Subsystem: If the subsystem is comprised of more than one element/component/box, this test level would be the integration and test of all the components as a subsystem.
- Element: Element-level testing is normally functional testing that verifies that the completed subassembly (multiple components) produces expected outputs from a given input. It validates that the element subassembly meets the requirements for further integration.
- Component/Unit/Box: Component-level test of the individual constituents of a subsystem.

System-level requirements will be verified at the system level after all underlying components have been verified and validated.

The IXPE AI&T effort is broken into 3 major segments, **Figure 16**. The spacecraft is assembled as a modular component in parallel with the payload module, and then the two are integrated into the full Observatory, which then goes through its own test flow.

Spacecraft integration and test covers the installation the components and units which make up the spacecraft. The order that spacecraft components are integrated onto the spacecraft structure is first defined by the flow of power into the vehicle. The first components to be installed are power and command & data handling (C&DH) followed by the first flight software (FSW) load. Once these central systems are installed, the rest of the spacecraft (ADCS components, telecom components, thermal components) can be integrated in any order, depending on hardware and/or personnel availability. The C&DH, GPS and telecom are crucial for timing. Once all the integration steps are complete, the team performs a dry-run of the Comprehensive Performance Tests (CPTs) for each major subsystem. This is also an opportunity to conduct the first Mission Scenario Test (MST) by allowing the MOC, located at the LASP at the University of Colorado-Boulder, to command the spacecraft and run a limited set of operations products.

The payload assembly and integration phase runs in parallel to spacecraft I&T. The payload is mounted to the spacecraft top deck. The three DUs are installed on their interface plates in their nominal positions on the +Z face of the top deck, and the DSU is installed on the -Z face. DU fiducials are verified against the boom fiducials. This is followed by installation of the DSU-to-DU harnessing. Concurrent with spacecraft top deck activities, the MMSS deck is integrated with its harnessing and thermal elements followed by MMAs. Optical alignment cubes will be used as “truth” in setting the Observatory boresight. Each of the MMAs is installed and precision aligned to the +Z star tracker. Once these two parallel paths are both complete, the MMSS module is integrated with the top deck assembly. This is done by interfacing the TTR to the MMSS center tube base and attaching the bipods to the retain and release mechanisms on the MMSS brackets. All harness interconnects are made and the X-ray shields are installed to the MMSS. Fiducials on the top deck, MMSS deck, boom ends, MMAs and DUs are used for positioning and critical alignments. The Payload Module then enters its functional testing and alignment phase.

The Observatory assembly and integration phase begins with the mechanical and electrical integration of the spacecraft and payload modules. The DU radiator and the solar array are then installed, completing the Observatory stack-up. The payload electronics and mechanisms are all tested and restowed, and then the solar array is deployed and removed in preparation for environmental testing. RF compatibility commanding is performed, followed by the pre-environmental baseline performance testing and an MST. The Observatory goes through EMI/EMC testing (complete), RF compatibility tests with the ground station infrastructure (complete), structural environmental testing (ongoing), and finally thermal vacuum/thermal balance testing in the deployed state. Following completion of environmental testing, all the baseline CPTs are repeated to verify all performance criteria are still met. Another MST is performed, and then the final closeouts are performed, followed by mass properties measurements and shipment to the launch site.

System Validation and Characterization

System validation characterization is part of observatory level testing and demonstrates the as-delivered system meets the system need, which means it addresses the concern; “Does ‘what was built’ meet the objectives?” System performance and functionality are validated over the nominal operating conditions and a more robust region of operation to develop performance margins. Risk management is used as a factor to establish V&V requirements while fault tree analysis (FTA) used to help populate V&V requirements and matrices. System validation testing includes:

- End-to-End Information System (EEIS) testing
- Comprehensive Performance Tests (CPT)
- Mission Scenario Tests (MST)
- Operational Readiness Tests (ORT)
- Mode transition testing

Characterization goes beyond straight V&V; its more than compliance ‘Yes’ or ‘No’. Characterization requires generation of data describing behaviors of selected hardware or software properties through Observatory testing or testing on the software test bench. Characterization data used to establish flight rules, calibrate the payload response, provide inputs for the Operations Handbook and generate boundaries for science data products. Characterization on IXPE includes testing at expected temperature limits in T-Vac, testing at expected electrical bus voltage limits, spacecraft and Observatory response testing to limited injected fault conditions and limits/off-nominal testing on the system test bed or Observatory to define capability boundaries. More detailed fault response testing is accomplished on the software test bench.

RISK AND OPPORTUNITIES MANAGEMENT

The IXPE Project implements a risk and opportunities management process[20] that includes methodologies for identifying, analyzing, planning, mitigating, monitoring, and tracking risks through the project lifecycle. As cost-capped, Class D, fast-paced (Formulation to Launch in ~4 years) mission, these methodologies are focused on providing project management the visibility needed to actively manage risks as well as the insight required for robust cost-based, risk-aware decision making.

The purpose of a risk and opportunities management process is to minimize the probability and impact of adverse events which threaten project objectives. To be successful, the process requires that all Project members actively engage in the process and ensure that risks are:

- Continuously identified throughout the Project life cycle
- Systematically analyzed using standardized criteria to determine impact and likelihood
- Appropriately prioritized to ensure the most effective use of Project resources
- Monitored and tracked to maintain an accurate Project risk profile and to evaluate the effectiveness of the RM process and risk related activities

These steps ensure the Project Manager can factor risk into day-to-day management of the Project and make effective cost-based, risk-aware decisions.

The Risk and Opportunities Management Board (ROMB) is the key Project risk management arena and includes members from all partners – systems engineers play a key role in the ROMB. Potential technical issues are often discussed at the PSET and submitted as risks when warranted to the ROMB. For the IXPE project, "risk" is defined as any scenario that, if/when encountered, may have a negative impact on the project's goals, objectives and/or technical outcome. Such scenarios may lead to degraded performance with respect to one or more performance measures (e.g., mission failure; inability to meet threshold mission requirements; exceeding mass or power limits, cost overruns, schedule slippage, etc.). Risk identification can occur at any point during the project lifecycle and all IXPE team members can identify risks to be brought forward to the ROMB.

Opportunities occur when a scenario is defined that may have a positive impact on the project's overall goals, objectives and/or technical outcome. Cost/schedule opportunities often come with some level of increased technical risk – for example, reduce the scope of a test (or eliminate a test) to reduce schedule albeit with some increase in technical risk.

Both Ball Aerospace and I2T have internal ROMBs which report risks up to the Project-level ROMB when internal risks reach certain thresholds according to cost, schedule and/or technical implications.

COVID 19 ACCOMMODATIONS

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

I2T had just completed instrument build and test as the Italian national shutdown started in March 2020. They were able to ship FM DU2 and the EM DU with EGSE prior to when 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 was able to get back into their laboratories and ship the final instrument elements in July 2020. COVID resulted in a multi-month delay in instrument delivery for AI&T at Ball.

MSFC, as a NASA center, was subject to the shutdown orders levied by NASA. NASA centers were largely placed on what's known as a Level 4 closure – nearly all on site work was stopped and nearly all personnel were not allowed on site. MMA #2 was complete; no testing had started at the time of the shutdown. Work at MSFC was able to resume on a task-by-task basis with approval starting in July 2020. Approvals were obtained and the build of MMAs 1, 2 & 3 is now complete. Calibrations are complete, the MMAs have gone through environmental testing and have been delivered to Ball for payload AI&T. COVID resulted in a multi-month delay in MMA delivery for AI&T at Ball.

Ongoing travel restrictions for both NASA and I2T personnel in general have resulted in assignment additional Ball work regarding the instrument and MMAs. Instrument efforts in the US are now performed by Ball. Ball became responsible for instrument receipt, unpacking, checkout, installation on the spacecraft top deck, payload and Observatory test along with calibration support at MSFC for telescope-level testing. Remote training by I2T is complete, instrument mechanical integration is complete on the payload deck at Ball and several instrument LPTs and CPTs have been run.

In addition, MMA work at Ball has also been assigned to Ball due to the MSFC travel restrictions. Added Ball responsibilities include MMA receipt, unpacking, checkout and inspections, and thermal shield installation. The MMAs are now installed in the MMSS deck and are aligned to the +Z star tracker.

The MMAs and instrument are fully integrated. The integrated instrument and MMAs have gone through observatory-level EMI/EMC and modal testing. These elements are ready for the upcoming structural environmental and T-Vac testing.

PROJECT CHALLENGES AND LESSONS-LEARNED

The distributed nature of the IXPE collaboration has presented opportunities and challenges. The challenges are assessed and become lessons-learned:

International partners

- Enabled the mission to occur due to detector technology
- Detailed Communications – verbal & written (goes both ways)

Team Communications

- Communication is key (IXPE mantras: "Over communicate" & "Assume good intentions")
- Cannot assume that all team members understood – even if they say yes
- Understanding is iterative and evolution is necessary
- Written communication has been effective for ensuring understanding

A Project wide tool for document archiving is required

- A cross-team tool is required for data sharing – access for all who need/want it
- Export regulations can complicate implementation – needs to be worked early
- Focus on maintaining assess capabilities as people move off/on the project

Late launch vehicle change – post CDR

- Updated Environmental Test Requirements
- Added vibe environment
- Added modal test requirement

- Added acoustics test requirement
- Changed thermal environment
- New interfaces (battery arming, envelope)
- Focus hard on LV ICD differences with Project LVIRD

Change tracking and control

- System Engineering Data Book construct effective for baseline definition, archiving and control
- Effective peer reviews with all mission partners

Other management priorities

- External pressures
- All technical folks across different organizations need to be aware of contract constraints

COVID 19 – reorganize work for remote compatibility

- Flexibility across teaming relationships
- Remote training of test teams and extensive use of remote connectivity used to overcome COVID-19 travel restrictions
- Early face-to-face meetings leveraged continued work during lockdowns.

MILESTONES AND PATH TO LAUNCH

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 has completed its Phase C activities with Ground System PDR completed in March 2019. All major procurements are complete; all hardware deliveries have been received at Ball. 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. Spacecraft and Payload I&T started in March 2020 and both are complete.

The Mission System Implementation Review (MSIR) occurred in September 2020. The Project transitioned from Phase C to Phase D in October 2020 with the NASA Key Decision Point D (KDP-D) review. Observatory integration and test started in December 2020. IXPE observatory level testing has completed modal testing, RF compatibility tests with Malindi and NEN/SN assets, and EMI/EMC testing. The Observatory is currently prepping for the start of low-level random and sine vibration testing. Launch is now planned for Fall 2021. Science operations are scheduled to last at least 2 years.

CONCLUSIONS

IXPE is a Class D Science Mission with many "Big" Program elements. IXPE is an international collaboration to conduct imaging x-ray polarimetry on a NASA Small Explorer – 3 separate telescopes. 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. Polarimetry & Imaging contribute new information to the understanding of the x-ray universe. Systems Engineering is critical in establishing the necessary relationships and processes for IXPE mission success. Cross-Team processes have been very successful in maintaining consistent baseline and tracking baseline as it evolves. Current SE activities are focused on V&V. The Project kicked off in February 2017. The Project transitioned from Phase C to Phase D in October 2020 with the NASA KDP-D review. All major flight elements are built, delivered to Ball and integrated into their respective modules. System-level environmental testing started in January 2021 with launch is foreseen in Fall 2021. The IXPE Project will conduct world-class science on a Small Explorers budget with a small satellite platform starting in the Fall 2021.

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