Imaging X-ray Polarimetry Explorer Mission Overview and Systems Engineering Status

Janice Houston
NASA Marshall Space Flight Center
Huntsville, AL 35812
(256) 714-1702
Janice.D.Houston@nasa.gov

William Deininger
Ball Aerospace
1600 Commerce Street
Boulder, CO 80301
(303) 939-5314
wdeining@ball.com

Ettore Del Monte
Istituto Nazionale di Astrofisica
Rome, Italy
[39] (064) 993-4675
ettore.delmonte@iaps.inaf.it

Jennifer Erickson
Ball Aerospace
1600 Commerce Street
Boulder, CO 80301
(303) 533-3170
jerickso@ball.com

William Kalinowski
Ball Aerospace
1600 Commerce Street
Boulder, CO 80301
(303) 939-7161
wkalinow@ball.com

***Abstract*— The Imaging X-ray Polarimetry Explorer (*IXPE*) is a space-based observatory that will have the capability to measure the polarization of X-rays from astrophysical sources. *IXPE* will improve sensitivity over OSO-8, the only previous X-ray polarimeter, by two orders of magnitude in required exposure time. *IXPE* will yield insight into our understanding of X-ray production in objects such as neutron stars as well as stellar and supermassive black holes. *IXPE* measurements will provide new dimensions for probing a wide range of cosmic X-ray sources—including active galactic nuclei (AGN) and microquasars, pulsars and pulsar wind nebulae, magnetars, accreting X-ray binaries, supernova remnants, and the Galactic center.**

Addressing NASA's Science Mission Directorate's science goal "*to probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter, and gravity*." *IXPE* will introduce the capability for X-ray polarimetric imaging, uniquely enabling the measurement of X-ray polarization with scientifically meaningful spatial, spectral, and temporal resolution. These polarization measurements will help answer fundamental questions regarding 1) the geometries of the flows, emission regions, and magnetic fields, 2) the physical process that lead to particle acceleration and X-ray emission, and 3) the physical effects of gravitational, electric, and magnetic fields at their extreme limits.

This scientific mission, *IXPE*, is being developed by the NASA Marshall Space Flight Center (MSFC), Ball Aerospace, the Italian Space Agency (ASI), the Institute for Space Astrophysics and Planetology (IAPS)/ National Institute of Astrophysics (INAF), the National Institute for Nuclear Physics (INFN), the University of Colorado Laboratory for Atmospheric and Space Physics (LASP), Stanford University, McGill University, and the Massachusetts Institute of Technology. The *IXPE* partners each provide unique capabilities and experience which are utilized to design, build and launch the *IXPE* observatory resulting in the collection of on-orbit scientific data measurements which are transmitted to ground stations and analyzed.

The established systems engineering (SE) methods and teaming approach to achieve the *IXPE* mission goals will be discussed. For this paper, the focus is the *IXPE* observatory and the collaboration of NASA MSFC, Ball Aerospace and IAPS/INAF. Our current focus is on requirements development and analysis along with definition of the interface control documents (ICD). Of particular note are requirements and ICDs between major flight elements and between organizations. This paper will describe the SE philosophy being used to ensure complete inter-organizational understanding and agreement as the Project moves towards SRR in September 2017 and PDR in June 2018. Current status and future milestones will be discussed.

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1. INTRODUCTION

NASA's Astrophysics Explorers Program selected the Imaging X-ray Polarimetry Explorer (*IXPE*) in January 2017 [10]. The mission cost is $188 million including the cost of the launch vehicle, post-launch operations, and data analysis [10].

IXPE is being developed by NASA MSFC, Ball Aerospace, the Italian Space Agency (ASI) with Institute for Space Astrophysics and Planetology / National Institute of Astrophysics (IAPS/INAF), the National Institute for Nuclear Physics (INFN) as major international partners, the University of Colorado Laboratory for Atmospheric and Space Physics (LASP), Stanford University, McGill University, and the Massachusetts Institute of Technology.

The IXPE Lead Systems Engineer (LSE), Chief Engineer (CE)/Project Systems Engineer (PSE), and Principle Investigator (PI) are provided by NASA MSFC. The MSFC PI provides the IXPE project management, project systems engineering, mission assurance, X-ray optics production, MSFC-based X-ray calibration activities, science data analysis, support for IXPE mission operations, and the IXPE Science Operations Center (SOC). IAPS/INAF and INFN in Italy will provide the IXPE detector system. Ball Aerospace will provide the IXPE Spacecraft, payload integration and Observatory AI&T. Ball/Colorado University (CU) Laboratory for Atmospheric and Space Physics (LASP) will provide mission operations.

The IXPE partners each provide unique capabilities and experience which are utilized to design, build and launch the *IXPE* observatory resulting in the collection of on-orbit scientific data measurements which are transmitted to ground stations and analyzed.

The established systems engineering (SE) methods and teaming approach to achieve the *IXPE* mission goals will be discussed. For this paper, the focus is the *IXPE* observatory and the collaboration of NASA MSFC, Ball Aerospace and IAPS/INAF. Our current focus is on requirements development and analysis along with definition of the interface control documents (ICD). Of particular note are requirements and ICDs between major flight elements and between organizations. This paper will describe the SE philosophy being used to ensure complete inter-organizational understanding and agreement as the Project moves towards SRR in September 2017 and PDR in June 2018. Current status and future milestones will be discussed.

There are also two companion papers at this conference: one details the IXPE observatory design [11] and the other covers the risk management process on IXPE [12].

2. *IXPE* MISSION

IXPE is an imaging X-ray polarimetry mission capable of measuring the X-ray polarization of a significant number of cosmic sources, including neutron star binaries, black hole binaries, Super Nova Remnant (SNRs) and an Active Galactic Nucleus (AGN) [1-6]. The overarching science goal of *IXPE* is to expand the understanding of high-energy astrophysical processes and sources in support of NASA's first scientific objective in astrophysics to discover how the universe works by expanding our understanding of high energy astrophysical processes.

IXPE is a straight-forward mission, comprised of payload which includes three X-ray telescopes with identical mirror modules and identical polarization-sensitive imaging detectors [7-8]. The mirror modules are based on nickel-cobalt replicated optics pioneered by MSFC and will be developed by MSFC in-house. The X-ray detectors were invented and developed by the IXPE Italian partners. The *IXPE* spacecraft (S/C), provided by Ball Aerospace, has substantial heritage [9].

Both the *IXPE* payload and the S/C are designed for modular fabrication and assembly. Figure 1 depicts the initial test flow. The IXPE detectors, filter wheel and payload flight computer undergo assembly, integration, functional and environmental testing, and calibration at IAPS and INFN. The X-ray mirror modules follow a parallel assembly, integration, and test path at MSFC. The detectors and mirror modules are then brought together for

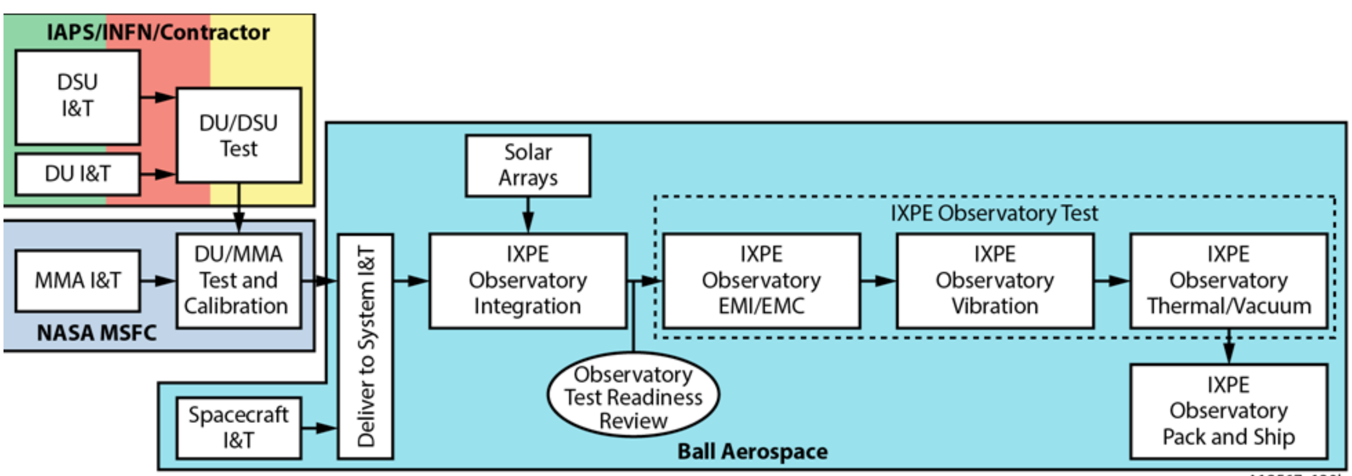

Figure 1. IXPE Test Flow

end-to-end X-ray testing and calibration at MSFC, and subsequently delivered to Ball Aerospace for payload assembly. In parallel to these activities, the S/C is assembled and tested. Observatory AI&T occurs when the assembled payload and spacecraft are integrated and go through environmental testing.

IXPE is planned to launch on a Pegasus XL Expendable Launch Vehicle (ELV) from the Reagan Test Site (RTS) at Kwajalein Atoll. The Observatory is designed for both stowed and deployed configurations as seen in Figure 2.

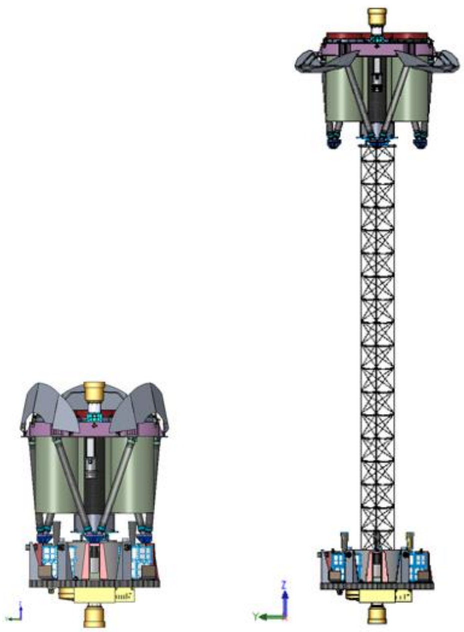

Figure 2. IXPE Observatory in Stowed and Deployed Configurations

The orbit altitude of 540 km was selected as the minimum to produce at least a 99% probability of a mission lifetime of greater than 2 years, while accounting for statistical variations in launch dispersions and solar activity. The effect of atmospheric drag will cause the orbit to change over the mission, resulting in small changes in eclipse duration, target viewing, and contact duration. These changes are all within the IXPE S/C and science margins for the baseline and extended mission.

IXPE operations enable simultaneous science data acquisition and communications with the ground. Communications do not require a specialized pointing profile because the passively coupled S-Band low gain antennas (LGA) provide a wide coverage pattern. The S-band telecommunications system downlinks the daily science and telemetry data up to 7.5 passes per day, ~700 Mbits/contact, out of the 15 passes available to the Malindi, Kenya ground station. The KSAT-sponsored Singapore ground station is used as backup. The navigation team at Laboratory for Atmospheric and Space Physics (LASP) maintains S/C orbital knowledge.

Science collection is coordinated to accommodate the downlink rate of 2 Mbps [11]. Command uploads can take place once every three days. Science data collection begins one month after launch with an uplink rate of 2 Kbps [11]. The science team generates and archives IXPE data products in HEASARC using proven algorithms.

The high level ConOps overview is illustrated in Figure 3.

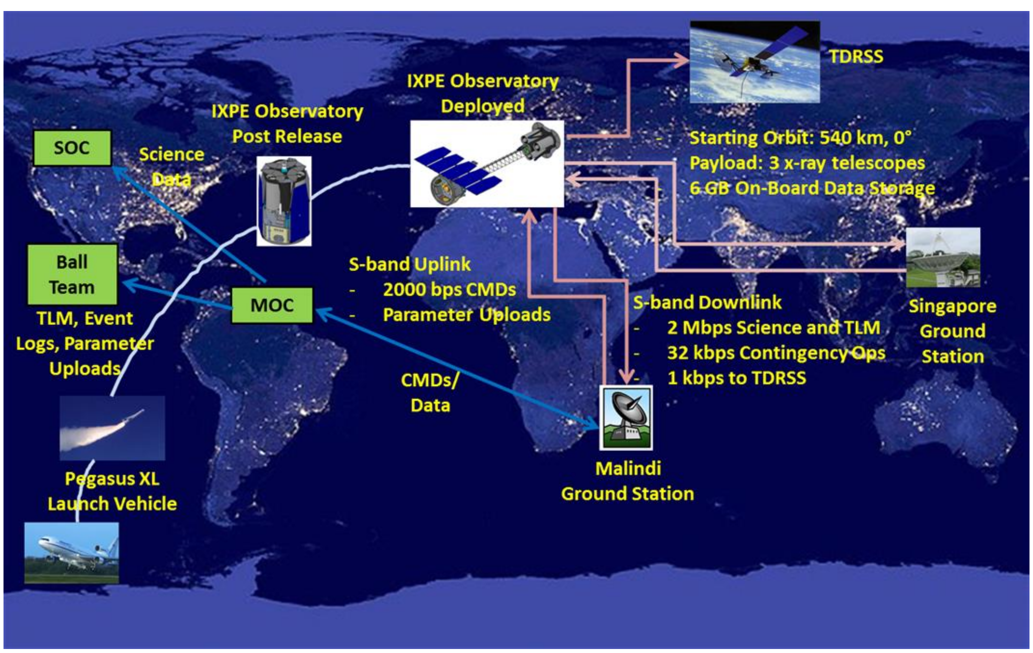

Figure 3. General IXPE ConOps.

Since IXPE has no propulsion system, the orbit will naturally decay during the mission and there are no consumable issues to worry about to maintain orbit. Orbit decay has no short-term effect on science return and mission operations. Drag will also cause the S/C to naturally deorbit within 25 years of the primary mission completion.

3. IXPE SYSTEMS ENGINEERING APPROACH

The IXPE systems engineering approach is multi-layered such that MSFC provides the overall Systems Engineering Management Plan (SEMP) and each partner manages to a compatible but partner-produced SEMP.

The IXPE Project Systems Engineering Team (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 with the systems the cost and schedule resources of the project. Each partner has a systems engineering representative on the PSET. The systems engineering tasks are tailored and shared by the whole IXPE project team.

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, central filing, 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 strongly encouraged. Regular face-to-face meetings are also utilized.

Requirements analysis and management

The IXPE requirements hierarchy is shown in the Figure 4 below. The IXPE Project documents mandatory requirements as *shall* statements down to level 3. These requirements are approved by the PI or the PI's designee and are managed by the PSE.

The program requirements on the IXPE Project such as cost limits, needed reserves, and launch dates for the Small Explorer (SMEX) projects are set forth 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. These Level 1 requirements have been submitted to SMD for approval.

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 will develop system requirements (level 3) from the science and project system requirements (level 2). These requirements will be controlled by the PSE and will be approved by the PSET.

Ball Aerospace and ASI will decompose Level 3 requirements to Level 4 and 5 requirements in their mission requirements documents.

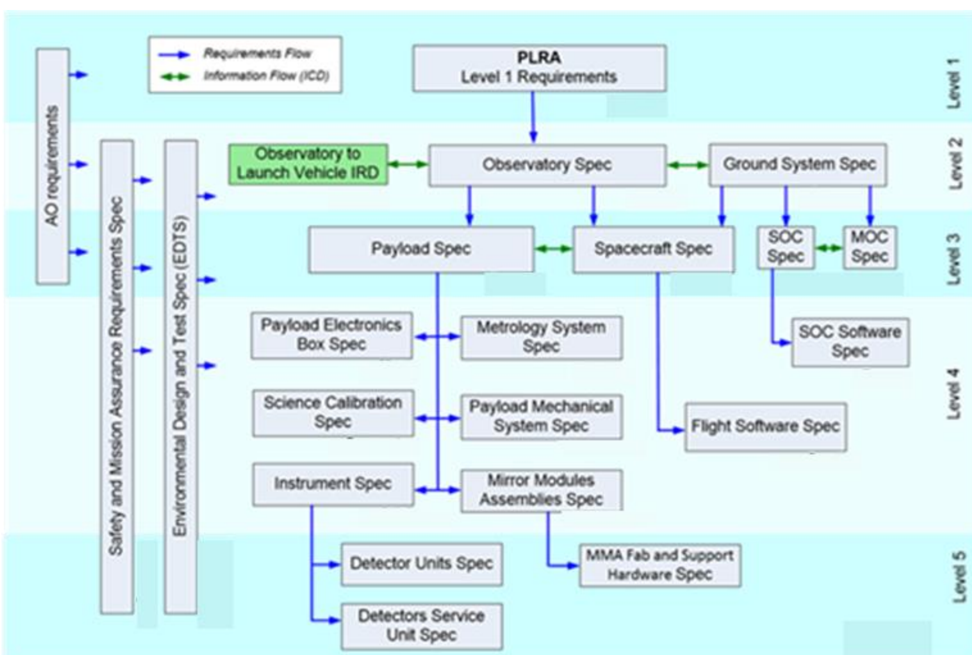

Figure 4. IXPE Requirements Hierarchy.

The science and project requirements and all system requirements will be captured in the DOORs requirements management tool. This tool will provide configuration control and will be used to implement the requirements traceability and verification matrices. The verification matrix will be utilized to confirm that all of the project requirements have been met and the project is ready for launch and operations. The IXPE requirements flow process per the PSET Charter is illustrated below in Figure 5.

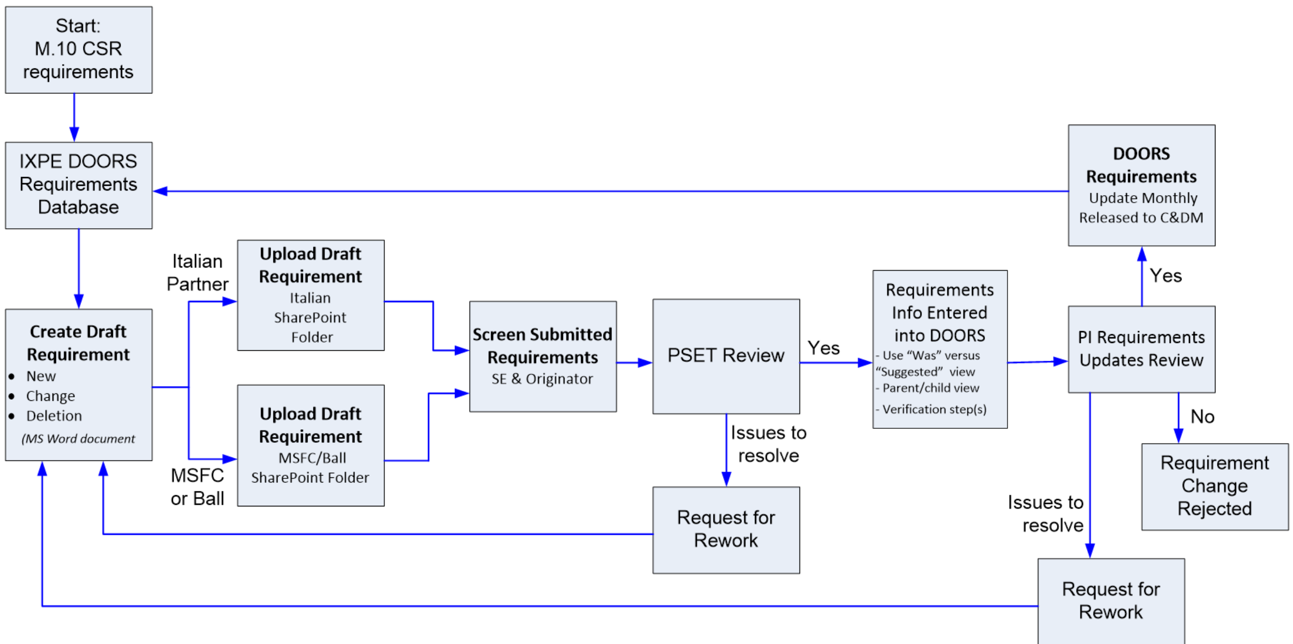

Figure 5. IXPE Requirements Flow Process.

Design and Interface Documentation

The PSET is responsible for documenting the project design and the intersystem level interfaces for the IXPE project. In general, the partner leading the subsystem is the owner of the interface control document (ICD). Of particular importance are two ICDs (1) the ICD between the instrument/Italian partners and the spacecraft/Ball partner and (2) the ICD between the complete payload assembly/MSFC and the spacecraft/Ball partner.

Design Trade Studies Process and Responsibilities

The PSE will maintain a list of all issues and design trade studies currently open on the project. 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. There will be dedicated working group meetings to work to close open design issues. All trade studies will be documented.

The PSE will be responsible for tracking all open issues and trade studies and capable of providing status (number open, and closure rate over time) at the monthly management reviews.

Risk Management

The IXPE risk strategy focuses on the achievement of highest priority objectives, while minimizing the mission risk profile [12]. Potential technical issues will be discussed at the PSET and submitted as risks when warranted to the Risk Management Board (RMB). The PSE and LSE are members of the RMB as are systems engineers from the IXPE partners. The goal of the risk management process is to identify risks proactively for mitigation before they are realized issues.

Resource Management

The IXPE PSET 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 will be given a fixed allocation at the start of the phase and margins will be tracked through design and implementation.

The PSE will identify mass, power, and other critical IXPE resource margins for the payload, the spacecraft, and the overall mission. The PSE 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.

Verification and Validation

A project level Verification and Validation (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 will be identified and tracked in a Verification Requirements Matrix (VRM).

The IXPE PSET is responsible for the planning of verification and validation of all requirements in Levels 1-3. Levels 1 thru 3 V&V will be planned and executed by the PSE with the support of the other systems elements as necessary. Level 2 verification closures will be approved by the LSE and PSE on formal verification closure notices (VCNs) after applicable lower level requirements are shown to have been verified. The partners will be responsible for developing and implementing V&V plans at the level 4 that are approved by the PSE. Finally, the PSE and LSE are responsible for tracking all unresolved V&V issues.

As part of the V&V process, a VRM will be developed that contains the complete set of items that need to verified or validated prior to launch. This matrix will be built from the project requirements and additional design features documented in the design documents which need to be verified. The project will track and report the progress of all V&V items as verification activities progress. Any action items from these issues will also be tracked by the project coordinator (PC) that notifies all late action item closures.

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. Appropriate verifications will be maintained and identified between the engineering test unit (ETU) and the flight unit.

Tailoring and Waivers

IXPE SE allows for tailoring and waivers. Waivers will be used to authorize a variance or noncompliance to a baselined design requirement.

Reviews

IXPE will be assessed technically at several reviews across its life cycle per the IXPE Project Review Plan. Major project reviews, including reviews of technical and programmatic status are included in the project Integrated Master Schedule (IMS). Key major Project reviews include: Systems Requirements Review (SRR), Preliminary Design Review (PDR), Key Decision Point C (KDP-C), Critical Design Review (CDR), KDP-D, Payload Integration Readiness Review (PIRR), Observatory Integration Readiness Review (OIRR), Payload Test Readiness Review (PTRR), Observatory Test Readiness Review (OTRR), Launch Readiness Review (LRR).

A SMEX assigned Standing Review Board (SRB) will govern the following IXPE reviews: SRR, PDR, CDR 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.

4. SYSTEMS READINESS REVIEW

The IXPE level 2 and 3 requirements shown in Figure 4 were confirmed at the project's systems requirements review (SRR) held in September 2017. The instrument system readiness review (ISRR) was held by the Italian partners in October 2017.

5. PATH TO PRELIMINARY DESIGN REVIEW

The IXPE mission PDR will be in June 2018. The path to PDR includes subsystem PDRs for the Spacecraft (March 2018) and the Payload (April 2018).

6. SUMMARY

The IXPE Systems Engineering team, comprised of partners from NASA MSFC, Ball Aerospace and IAPS/INFN are using established systems engineering methods and teaming approach to achieve the IXPE mission goals. The IXPE requirements have been reviewed by an independent review board during Systems Requirements Review. The IXPE SE team focus is now on PDR, with subsystem PDRs scheduled for Spring 2018 and the mission PDR in Summer 2018.

ACKNOWLEDGEMENTS

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Biography

Janice Houston *is currently the Lead Systems Engineer for the IXPE mission. She received a B.S. in Astronomy and Physics from the University of Arizona in 1993. During her 20+ year career, her projects have resulted in spaceflight hardware on sounding rockets, Space Shuttle, and International Space Station. She has worked on ALV X-1 and Ares I-X launch vehicles, SWORDS and SLS development vehicles, and ASMAT and SMAT subscale rocket test programs. She has flown on the "Vomit Comet", holds two patents for her experimental work with magnets in the microgravity environment, and has co-authored multiple papers. She has served on the University Of Arizona Physics Department External Advisory Board and two National Research Council Transportation Research Board Airport Cooperative Research Program panels. Prior to NASA MSFC, she worked at Jacobs and The Boeing Company.*

William Deininger *is a staff consultant in systems engineering for Ball Aerospace. Dr. Deininger currently is the Ball Chief Systems Engineer (CSE) and Payload Lead on the NASA IXPE Project. He is also the Chief Engineer on the Green Propellant Infusion Mission. Recent work has included serving as the Ball CSE on the NEOCam Phase A Study, PI and systems lead for the Solar Electric Propulsion Technology Demonstration Mission study and systems lead for the CPST Mission study, all 3 for NASA. He was the functional manager for the Mission Systems Engineering group at Ball Aerospace for 2 years* *and, prior to that, the Kepler Flight Segment Manager. He was also the Chief Systems Engineer on the Mars Micromissions and StarLight Projects. Prior to joining Ball Aerospace, Dr. Deininger worked at FiatAvio-BPD in Italy for 9 years, as a Member of the Technical Staff at JPL for 8 years, and at Argonne National Laboratory for 1½ years. He is an Associate Fellow of AIAA, Senior Member of IEEE and was awarded 2017 Engineer of the Year by the Rocky Mountain Section of the AIAA. He received a Dottorato di Ricerca (Ph.D.) in Aerospace Engineering from the Università degli Studi di Pisa in Italy, an M.S. in Plasma Physics from Colorado State University, and a B.S. in Physics from the State University of New York at Cortland.*

***Ettore Del Monte** received his Ph.D. in Astronomy in 2005 at the University of Roma "Tor Vergata" (Italy).He worked in the development and qualification, integration and calibration of the SuperAGILE X-ray instrument on the AGILE satellite mission, launched in 2007. After AGILE, he worked in proposals for satellite-borne X-ray instrumentation like the Large Observatory For x-ray Timing (LOFT) and the X-ray Imaging Polarimetry Explorer (XIPE). 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).*

Jennifer Erickson received the B.S in engineering from the Colorado School of Mines, Golden, CO, USA in 2006 and the M.S. in engineering systems from the Colorado School of Mines, Golden, CO, USA in 2008. From 2006 to 2008, she was a Research Assistant. From 2008 to 2011, she was an RF Design Engineer. Since 2011, she has been a Systems Engineer with Ball Aerospace, Boulder, CO, USA. Her research interests included biotelemetry systems in artificial human hips and integrated circuits. Ms. Erickson was awarded a patent for "Antenna System with Integrated Circuit Package Integrated Radiators" in 2010 and the Outstanding Graduating Senior from the Colorado School of Mines in 2006.

***William Kalinowski** is an Electrical Systems Engineer at Ball Aerospace and is currently the IXPE spacecraft bus lead systems engineer and the IXPE command and data handling subsystem lead. Before coming to Ball Aerospace, he 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.*