IXPE
Imaging
X-Ray
Polarimetry
Explorer

Imaging X-Ray Polarimeter Explorer Systems Engineering Approach and Implementation

SSC21-II-01

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Ball Aerospace

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Mission Operations & Autonomy

SmallSat Session: Next on the Pad

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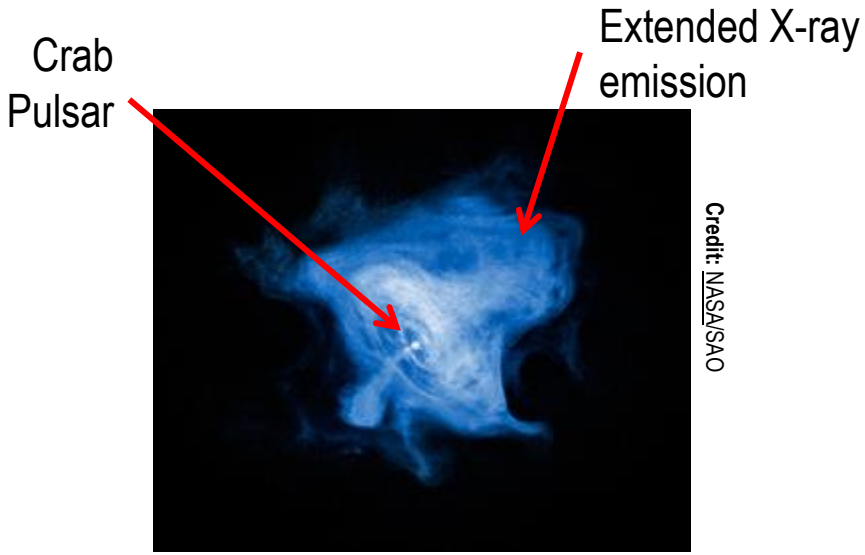
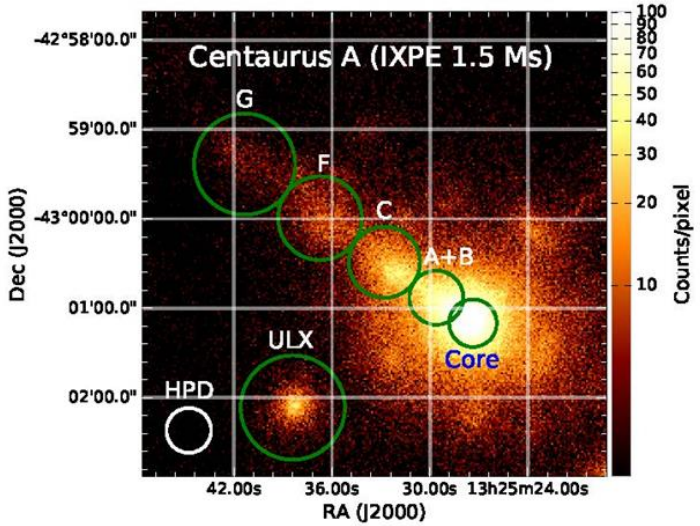
IXPE Science – A Unique Step Forward; Dedicated Mission

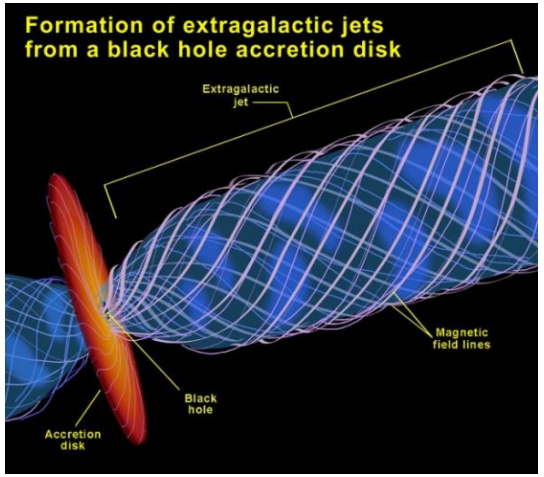
- **X-ray emission occurs from energetic processes: In-fall of matter into Neutron Star or Black Hole, synchrotron or shock emission, or very hot regions**
  - Can originate both from point and extended sources; ***Imaging*** separates these sources
  - ***Polarization*** of X-rays occurs if there is anisotropy in emission geometry or mag field, plasma reflections, or general relativistic effects



Imaging separates regions with different emission mechanisms

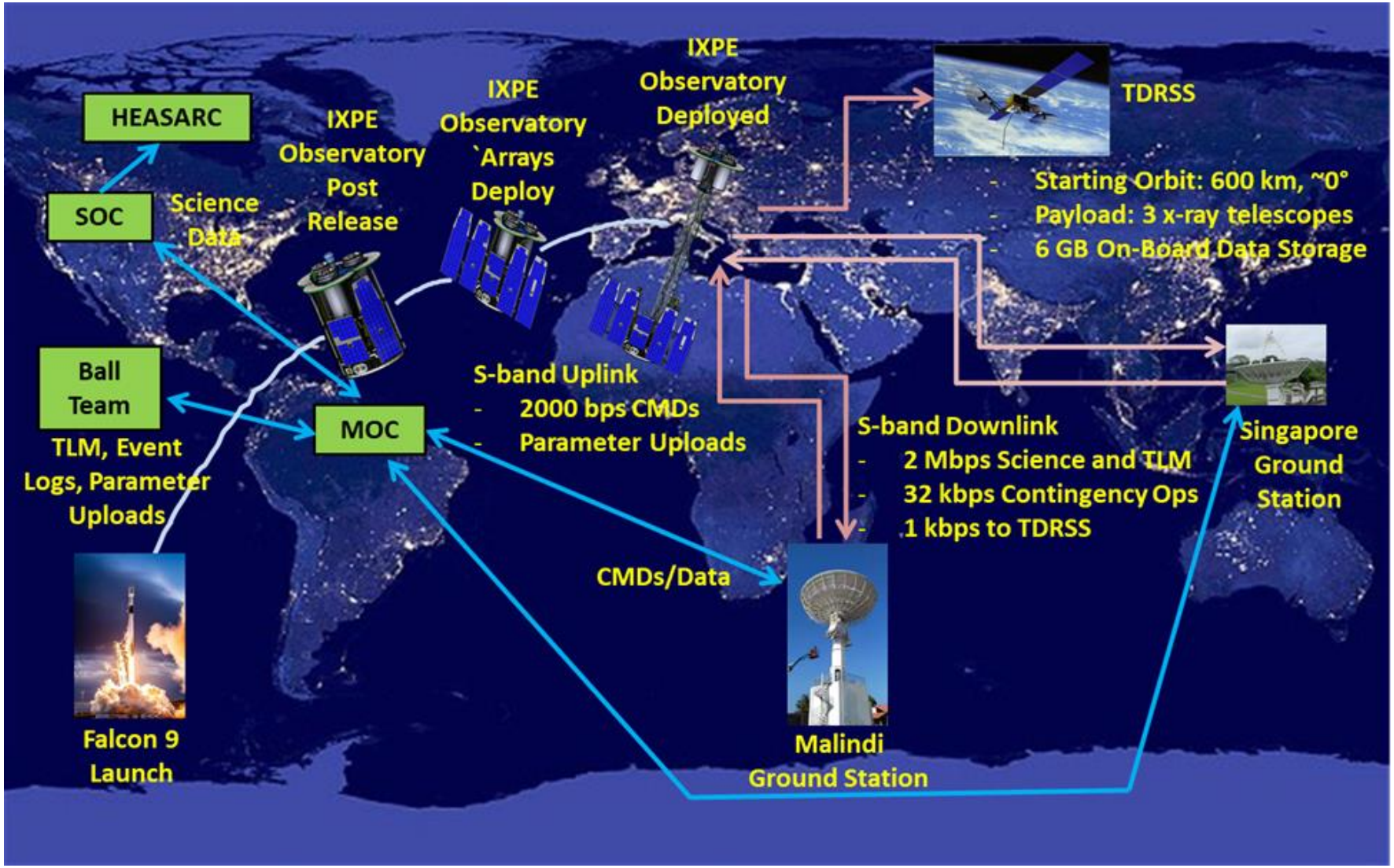


HPD *enables imaging capability → probe mag field geometry along jet*



Polarization probes the source geometry and mag field strength

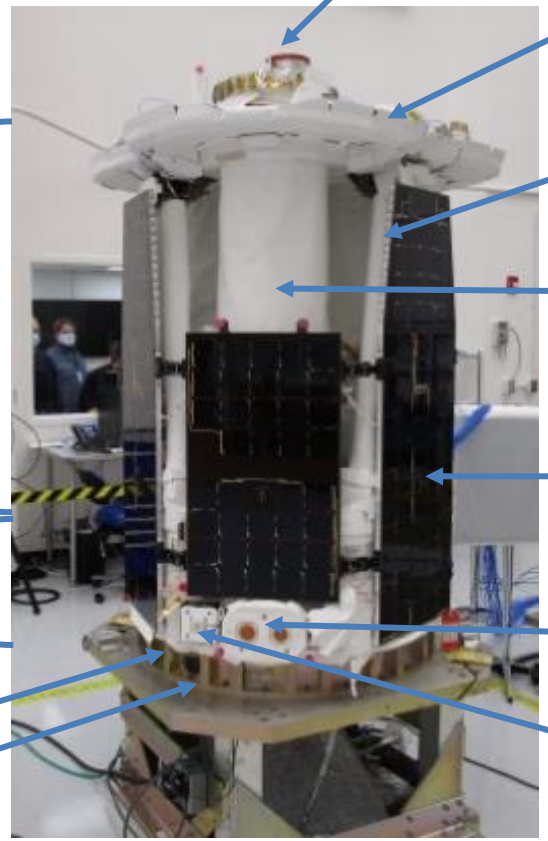
General IXPE CONOPS Overview



- Cape Canaveral launch
- Falcon 9 LV
- 2 deployments, both during contacts
- TDRSS for early ops
- Malindi & Singapore ground stations
- MOC – CU/LASP
- SOC – MSFC
- Data archive - HEASARC

IXPE Observatory – Stowed & Deployed

2.1m Tall
1.2m Across



PAYLOAD

SPACECRAFT

+Z Star Tracker

Fixed X-Ray Shield

Bipod (3)

MMA (3)

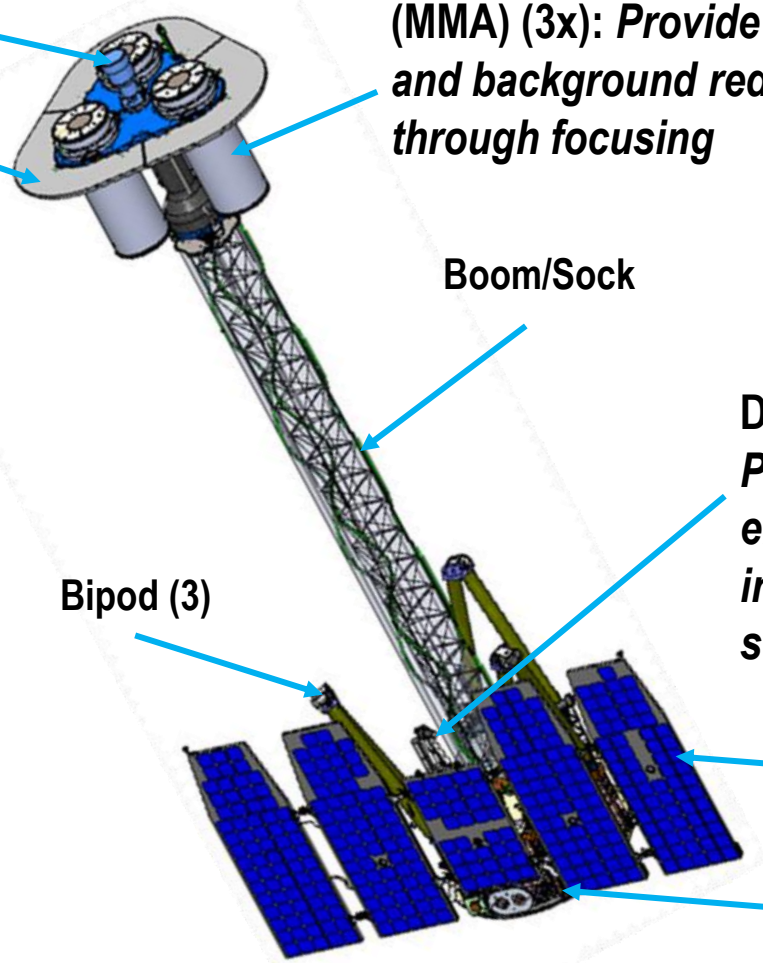
Stowed Solar Array

S-Band LGA (2)

GPS Antenna (2)

Separation Plane

5.2m Total Length



Mirror Module Assemblies (MMA) (3x): *Provide imaging and background reduction through focusing*

Boom/Sock

Detector Units (DU) (3x) *Provide position, energy and polarization information plus time stamp*

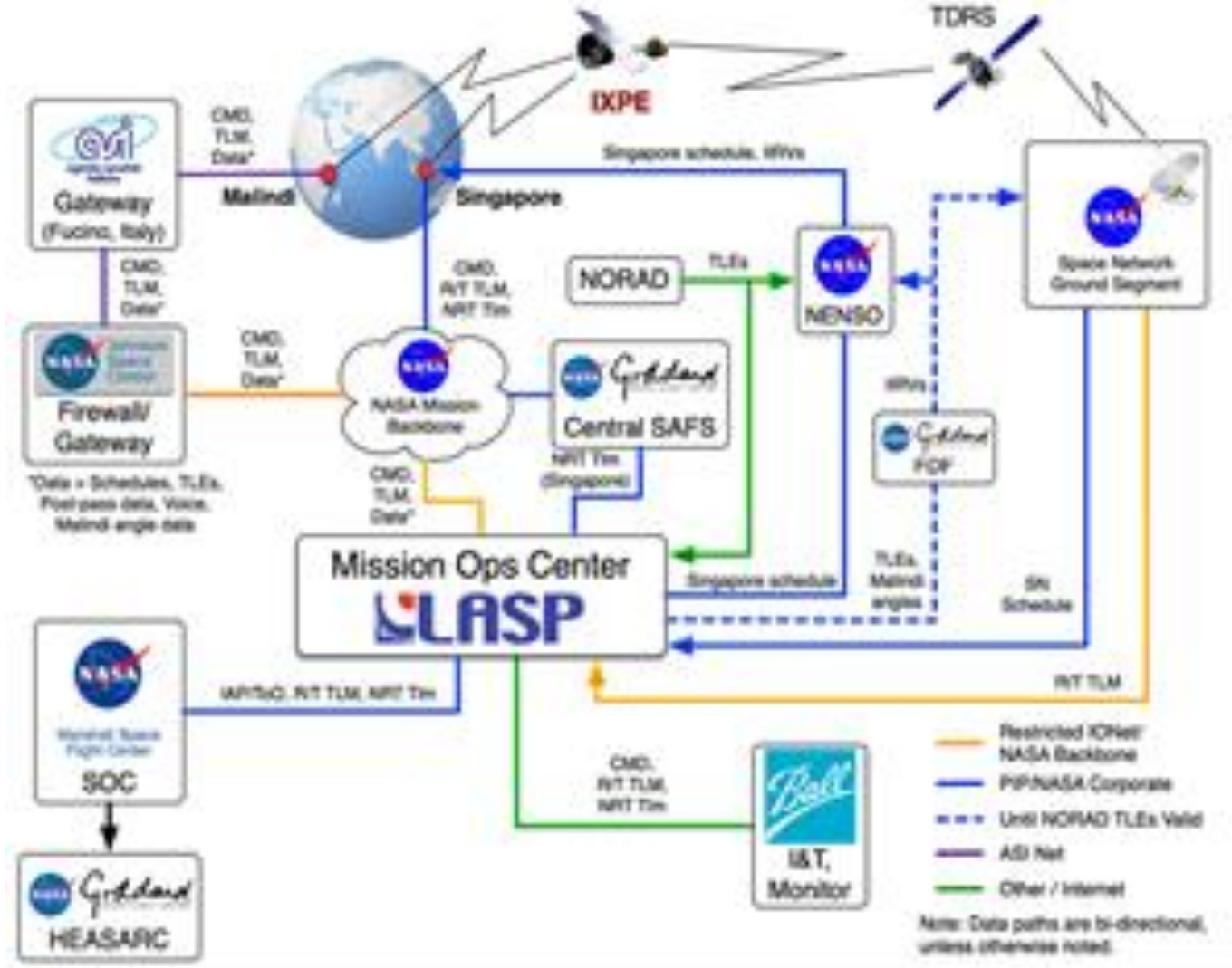
Bipod (3)

Deployed Solar Array

IXPE Spacecraft

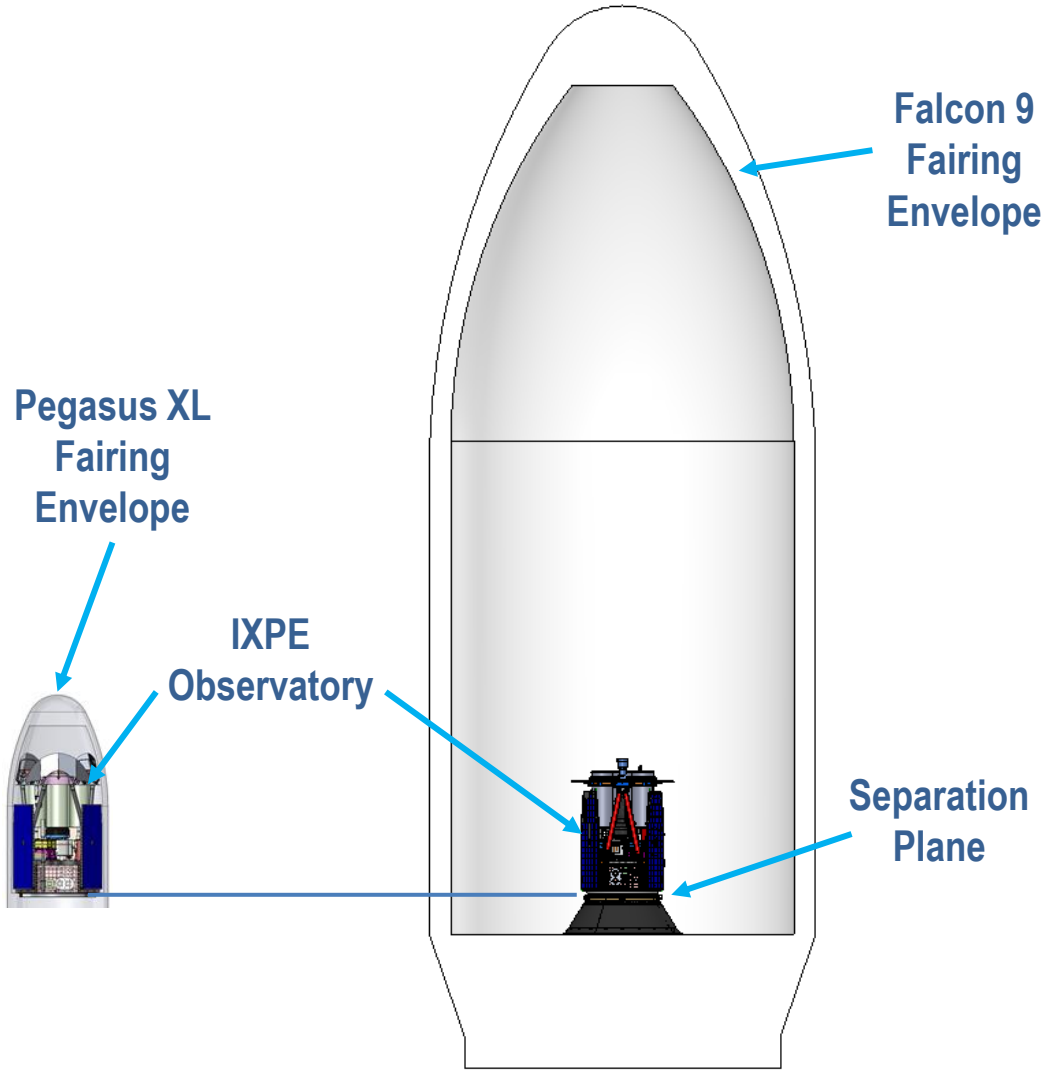
IXPE: Ground System Network Architecture Overview and Interfaces

- SOC at MSFC
  - Data archive at HEASARC at GSFC
- MOC ay CU/LASP
  - Managed by Ball
- ASI provides primary ground station at Malindi
- Backup ground connectivity
  - NEN Singapore
  - SN TDRSS



IXPE in Stowed Configuration for Launch
Packaged within a Pegasus XL Fairing in Comparison to a Falcon 9 Fairing

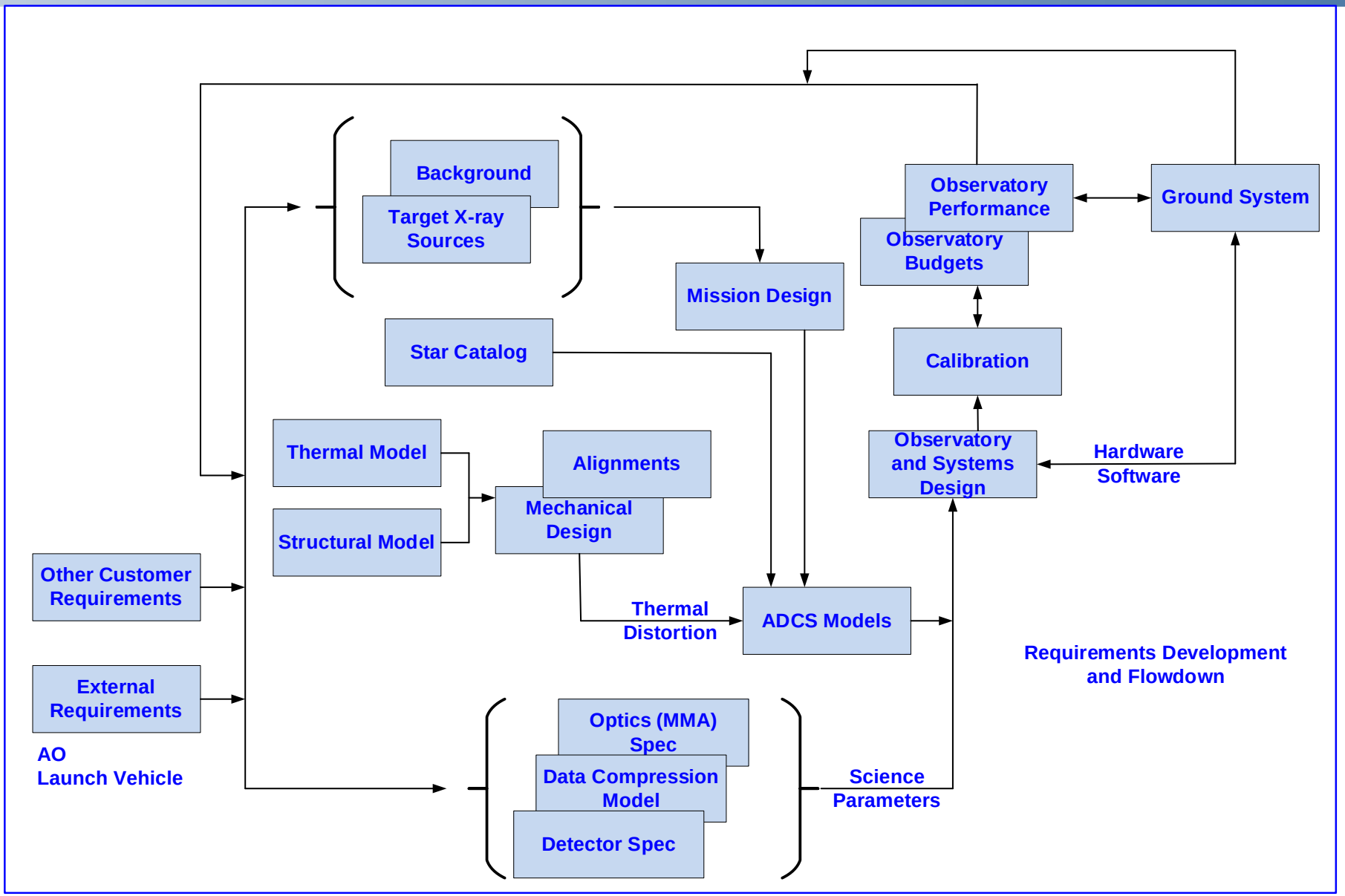
- At time of selection (Feb 2017), Pegasus XL only choice for ~0 degree inclination orbit
- Dedicated launch, mass constrained
- Observatory powered at launch
  - C&DH (FSW in launch mode)
  - S-band Command Receiver
  - Magnetometer
- Falcon 9 selected in July 2019
  - Longer coast phase
  - Higher altitude (540 km → 600 km)
  - Environments
    - Structural
    - Acoustics
    - Thermal
    - EMI/EMC
  - Battery Arming Relay Assembly
  - Move to fixed x-ray shield
    - Eliminate mechanisms



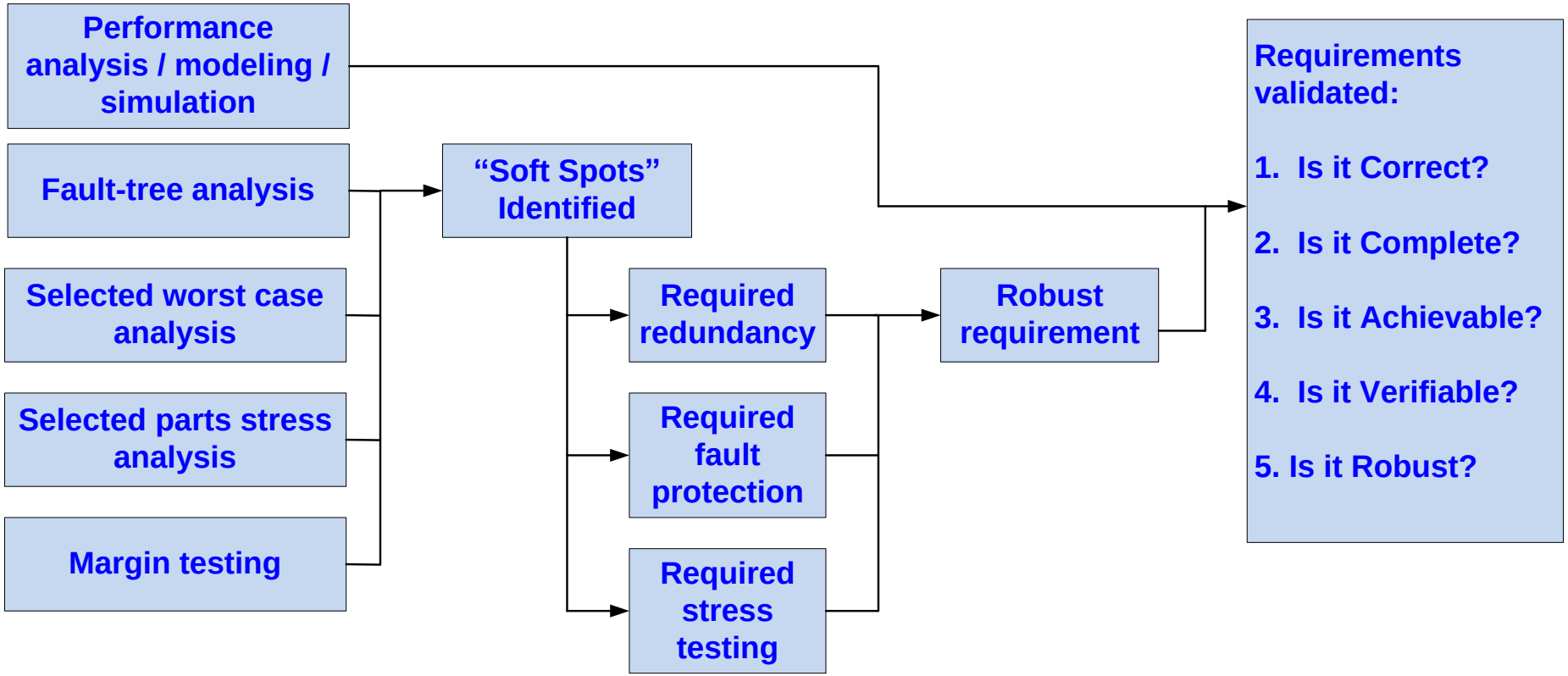
IXPE System Engineering Principals

- Project uses established systems engineering (SE) methods and tailored teaming approach to achieve IXPE mission goals – Particularly important for the dispersed team building, testing and operating IXPE
- Requirements management and interface control key on IXPE
- Systems work is now focused on requirements maintenance, requirements verification and validation via sell-off packages (SOP), interface control document (ICD) verification
- The Project Systems Engineering Team (PSET) is the key IXPE SE forum
  - The PSET includes members from MSFC, I2T and Ball
  - Key PSET responsibilities include requirements/verification analysis and management, design and interface management, technical resource management, design trade studies, technical risk identification and document approval
- IXPE developed 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 include instrument and MMA requirements/verification analysis and management, instrument and MMA interface management, instrument and MMA technical resources assessment, technical risk identification
  - Instrument and MMAs delivered, Payload SE Technical Team efforts focus on assessments as testing progresses

IXPE Requirements Definition Flow



IXPE Requirements Development



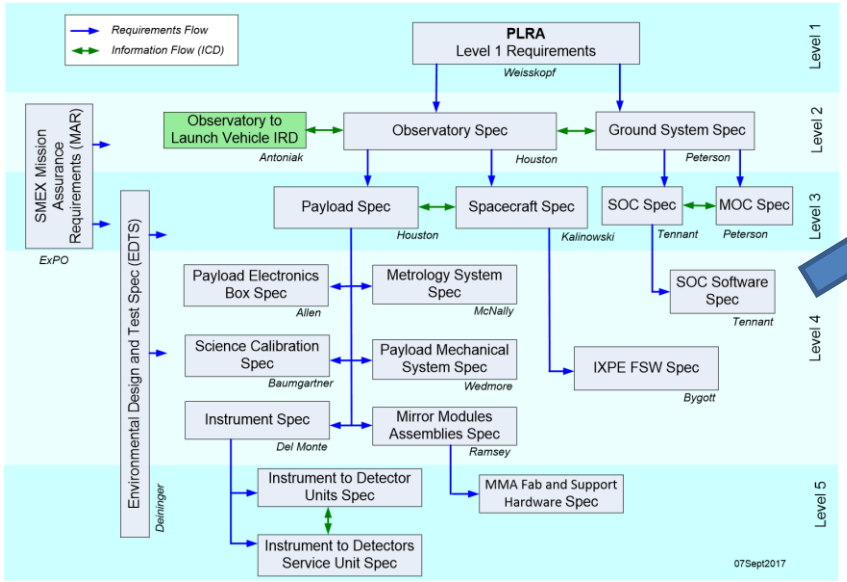
IXPE has had minimal ripple in Level 1 requirements since the completion of the Phase A activities (Concept Study Report (CSR))

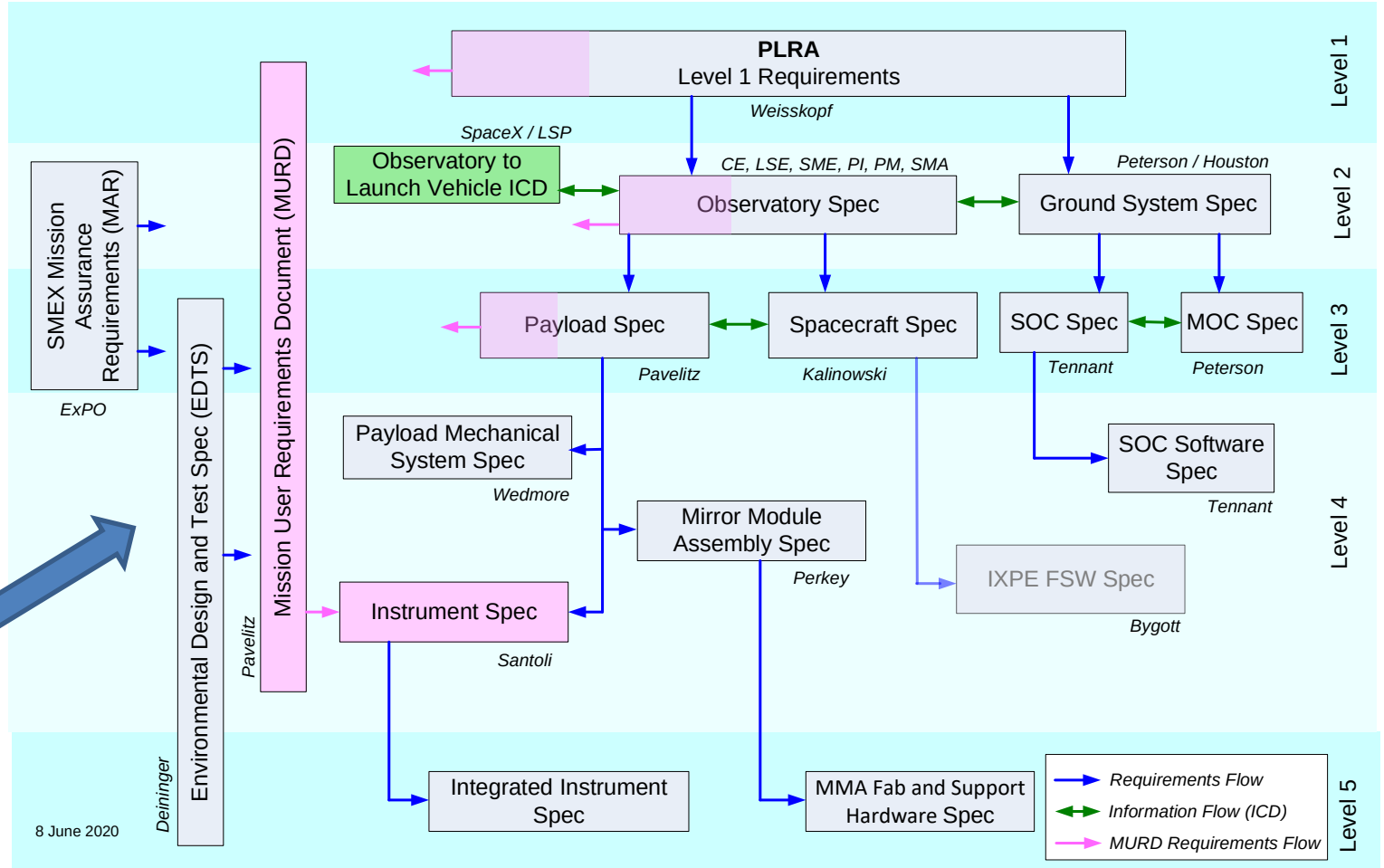
For requirement validation there are five major elements:

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

IXPE Requirements Hierarchy Evolution

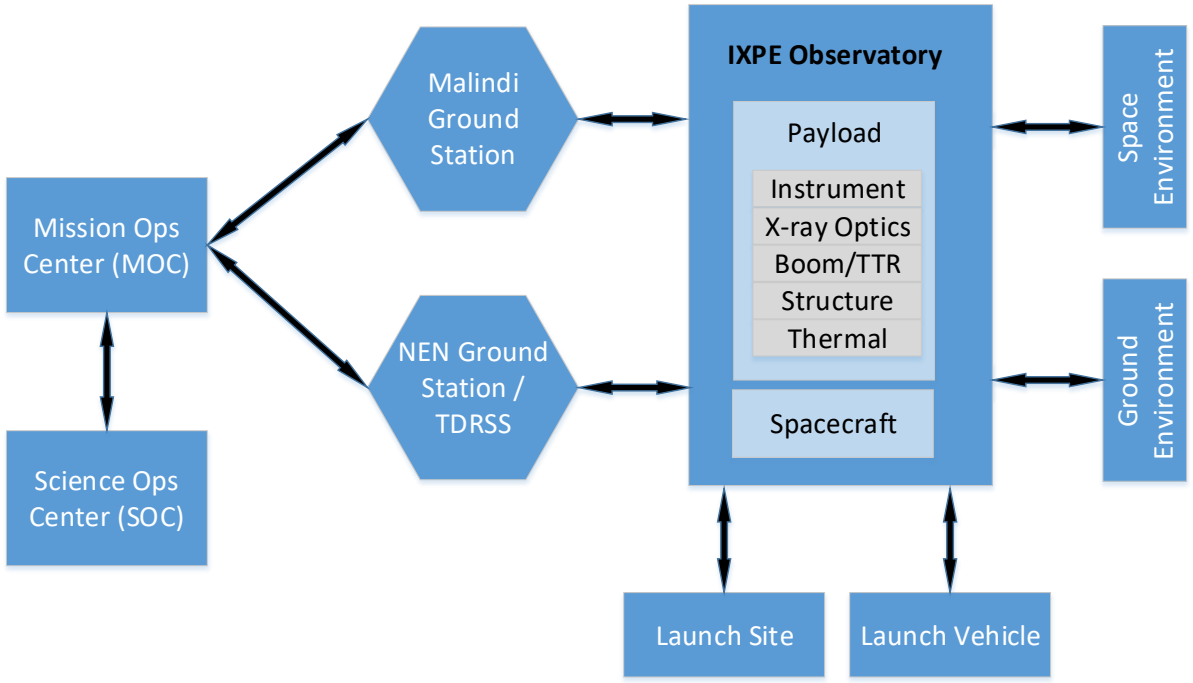
- Original spec tree overcome by international partner needs → created requirements document for ASI to flow to Instrument team
- Created special document (MURD) with Instrument related Level 1, 2, & 3 requirements flowing to Instrument Spec
- Requires coordination to make sure these requirements are in sync with IXPE DOORS requirements database



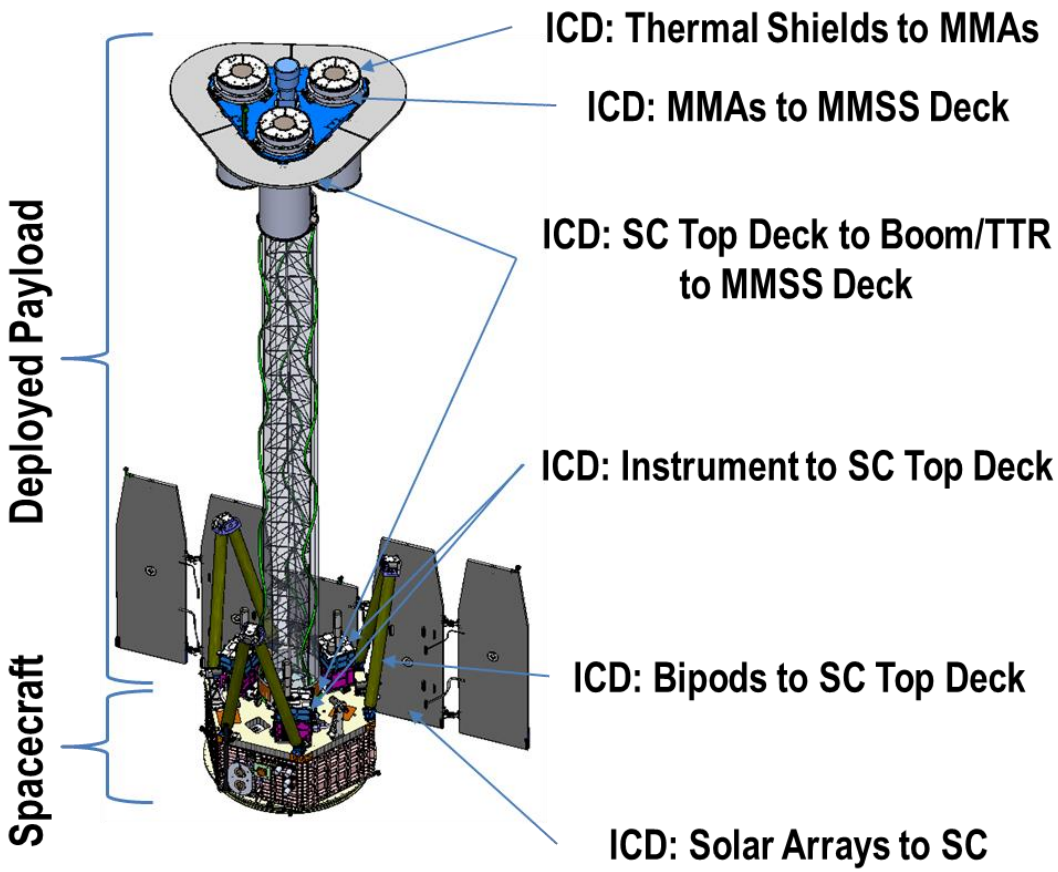


IXPE Requirements Ownership and Flow-Down Is Defined; Requirements Mature

IXPE Flight System Interfaces

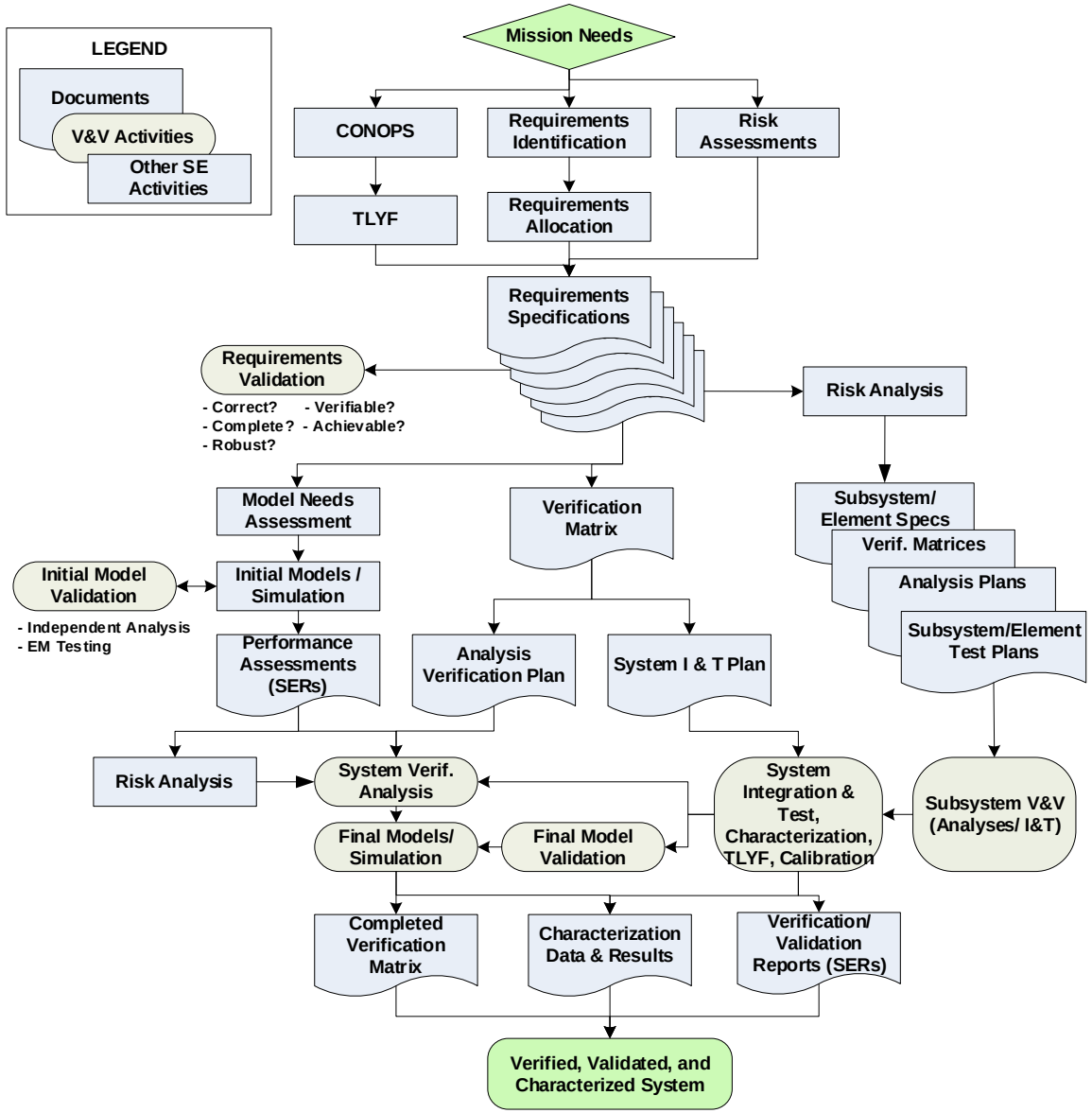


IXPE Flight Segment Internal Interfaces



IXPE Verification, Validation and Characterization (V&V) Activities

- Rigorous and iterative V&V process essential to ensuring successful realization of reliable & cost effective IXPE Mission System
- Verification, Validation and Characterization(V&V) activities done to provide objective evidence that IXPE meets
  - Design requirements
  - Stakeholders' needs
  - Ready for mission
- Overall, IXPE's V&V philosophy integrates and verifies at lowest level possible considering cost, schedule, & technical impacts with associated risks
  - IXPE V&V process, part of SE process, starts at component/unit level and rolls up to appropriate higher levels
- V&V compliance assured by collaborative development by V&V Team which spans all project organization
- Proof in form of traceable, detailed evidence of compliance at every level, rolling up to and including the overall system and architecture levels
- V&V activities on the IXPE Project consist of:
  - Requirements validation
  - Development and validation of models, algorithms and Simulations
  - Verification of each system-level requirement
  - Characterization of key observatory, spacecraft and payload performance parameters
- V&V process provides a framework to show that all needs and expectations are met by as-built system



System Integration and Test Levels and V&V

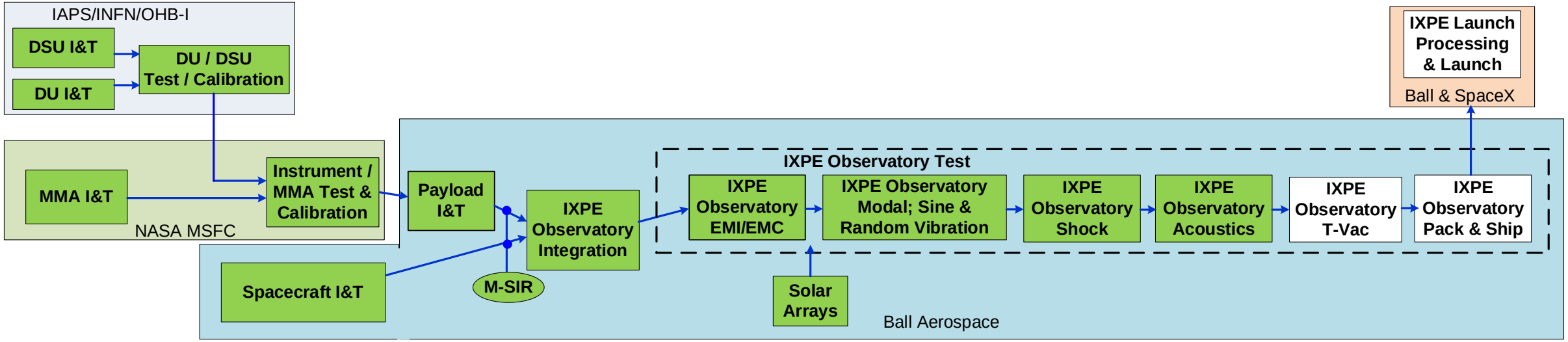
- **IXPE AI&T effort broken into 3 major segments:**
  - **Spacecraft module**
  - **Payload module**
    - **MMSS Deck Element**
    - **Top Deck Element**
  - **Brought together to form Observatory**

Assembled in parallel

Complete

System Validation:

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



Project Challenges & Lessons Learned

- International partners
  - Enabled the mission to occur due to detector technology
  - Detailed Communications – verbal & written (goes both ways)
- Team Communications 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
- Project Tool for document archiving (SharePoint)
  - A cross-team tool is required for data sharing – access for all who need/want it
  - Export regulations can complicate implementation
- Late launch vehicle change
  - 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
- Other management priorities
  - External pressures
- COVID 19
  - Flexibility
  - Remote training of test teams & extensive use of remote connectivity used to overcome COVID-19 travel restrictions
  - Early face-to-face meetings leveraged continued work during lockdowns

Project Summary and Conclusions

- **IXPE is an international collaboration to fly imaging X-ray polarimetry on a NASA Small Explorer – 3 separate telescopes**
  - Use X-ray polarimetry to examine several categories of cosmic X-ray sources: from neutron stars and stellar-mass black holes, to supernova remnants and active galactic nuclei: Polarimetry & Imaging
- **IXPE is a Class D Science Mission with many "Big" Program elements**
- **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**
- **Systems Engineering has played a key role in IXPE Project execution**
- **Project in Phase D – Environmental Testing Phase; SE activities focused on V&V; tracking to Fall 2021 launch**
- **IXPE Project will conduct world-class science on a Small Explorers budget with a small spacecraft**

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- The work described in this presentation is a culmination of efforts from teams at NASA MSFC, Ball Aerospace, ASI, INAF, INFN, CU/LASP, Stanford, McGill University and Università degli Studi di Roma Tre

Thank You – For More Information

THANK YOU

- https://www.ball.com/aerospace
- https://ixpe.msfc.nasa.gov/
- IXPE | http://www.iaps.inaf.it

IXPE Payload

Focus X-rays using

↓

Set of three mirror module assemblies (MMA)

↓

Onto three corresponding gas pixel detector units (DU)

↓

Co-aligned with +Z star tracker

↓

With focal length of 4.000 m established by boom