IXPE mirror module assemblies

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ABSTRACT

Expected to launch in 2021 Spring, the *Imaging X-ray Polarimetry Explorer* (IXPE) is a NASA Astrophysics Small Explorer Mission with significant contributions from the Italian space agency (ASI). The IXPE observatory features three identical x-ray telescopes, each comprised of a 4-m-focal-length mirror module assembly (MMA, provided by NASA Marshall Space Flight Center) that focuses x rays onto a polarization-sensitive, imaging detector (contributed by ASI-funded institutions). This paper summarizes the MMA's design, fabrication, alignment and assembly, expected performance, and calibration plans.

Keywords: X-ray astronomy, grazing-incidence optics, electroformed optics, mirror alignment and assembly, polarimetry

1. INTRODUCTION

The *Imaging X-ray Polarimetry Explorer* (IXPE)[1,2] will be the first x-ray astronomy mission dedicated to polarimetry. Optimized for polarimetry at 2–8 keV, IXPE will measure the (linear) polarization of various types of neutron stars, blackhole systems, active galactic nuclei, and supernova remnants. Planned to launch in 2021 Spring for a baseline two-year mission, IXPE is a NASA Astrophysics Small Explorer (SMEX) mission in partnership with the Italian Space Agency (Agenzia Spaziale Italiana, ASI) and with prime contractor Ball Aerospace.

Previous papers[3,4] provide a technical overview of the entire IXPE mission—including the flight system ("Observatory") and the ground system. The present paper provides an overview of the IXPE x-ray telescope system (§2) and describes in more detail its x-ray mirror module assemblies (§3).

2. TELESCOPE SYSTEM

Figure 1 shows the IXPE Observatory—comprising the Spacecraft and the Payload. The Spacecraft supports non-mission-specific functions and also includes features that enable operation of the flight system as an astronomical observatory: reaction wheels and magnetic torquers for 3-axis-stabilized (non-propellent) pointing, (fore and aft) star trackers to determine pointing direction and roll in celestial coordinates, and a GPS receiver to provide positional information and to establish a stable reference for accurately time tagging x-ray events.

The IXPE Payload is the x-ray telescope system: three x-ray telescopes, each with an x-ray mirror module assembly (MMA) and a polarization-sensitive detector unit (DU), separated by a shared optical bench—a boom deployed to match the 4-m focal length of the x-ray optics. Additional Payload components support operation of the telescopes. For purposes of discussion of Figure 1, it is convenient to group components of the x-ray telescope system into the optics (§2.1), the instrument (§2.2), and the optical bench (§2.3).

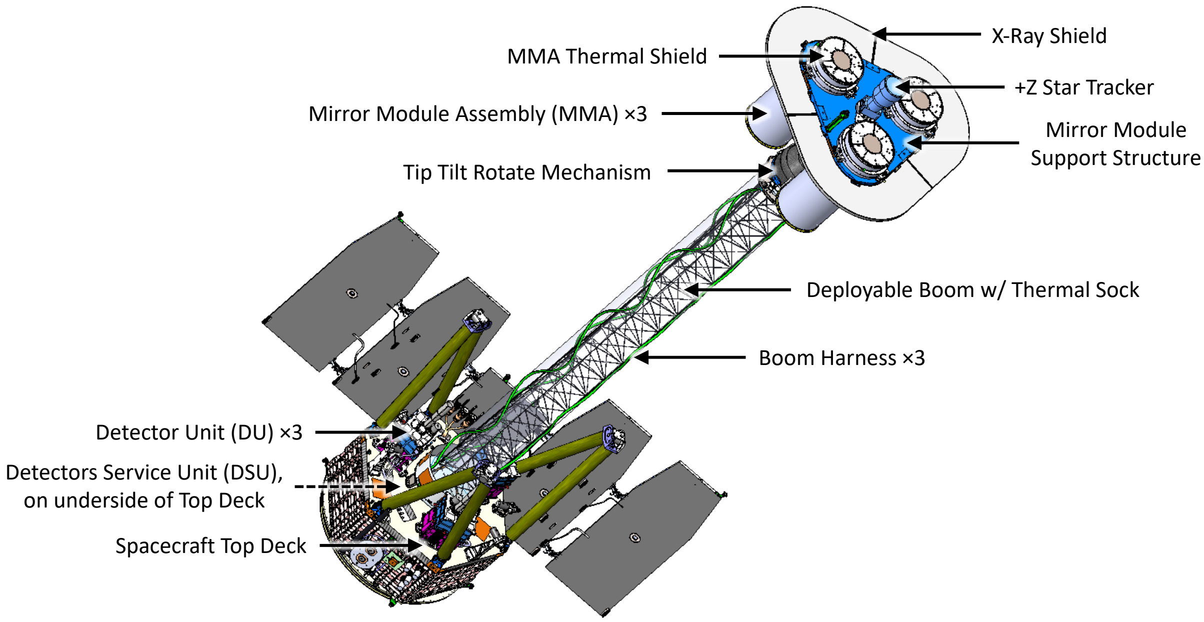

Figure 1. IXPE Observatory with elements of the scientific Payload—i.e., the Telescope System—identified. Ball Aerospace is responsible for alignment, assembly, integration, and testing of the Observatory. [Ball Aerospace]

2.1. Optics

The x-ray optics comprise 3 mirror module assemblies[5] (MMAs, §3), with optical axes co-aligned to the Spacecraft's +Z star tracker. These are mounted on the mirror-module support structure (MMSS), which is skirted by an x-ray shield to preclude direct illumination by celestial sources of the focal planes of the collimated detector units (DUs). (The -Z star tracker and the single star-tracker electronics box are mounted to the bottom side of the Spacecraft top deck.) NASA Marshall Space Flight Center (MSFC) is responsible for the MMAs, which are covered on each end by an MMA thermal shield, contributed by Nagoya University (Japan). Ball Aerospace is responsible for the other components of the Optics subsystem—including the MMSS and its center tube, the x-ray shield, MMA heaters, and the bipod struts and launch locks that support the MMSS in the Observatory's stowed configuration.

2.2. Instrument

The x-ray instrument comprises 3 polarization-sensitive detector units[6,7] (DUs), each aligned to its respective MMA node, plus a detectors service unit (DSU) that provides control and data handling for the DUs. Each DU is mounted through an interface plate to the top side of the Spacecraft top deck, while the DSU is mounted to the bottom side of the top deck. A large triangular-shaped radiator near the aft end of the Spacecraft cools the DUs. ASI is responsible for the DUs and DSU through the Italian Instrument Team—principally, the Istituto Nazionale di Astrofisica (INAF) Istituto di Astrofisica e Planetologia Spaziali (IAPS), the Istituto Nazionale di Fisica Nucleare (INFN) Pisa, and the contractor OHB Italia SpA (OHB–I). Ball Aerospace is responsible for the other components supporting the Instrument subsystem—including the interface plates, thermal straps and radiator, and command and data handling interfaces between the DSU and the Spacecraft's Integrated Avionics Unit (IAU).

2.3. Optical bench

A deployable boom serves as the telescope system's optical bench, enveloped by a thermal sock to minimize thermally induced distortions. Connecting the boom to the MMSS center tube is a Tip–Tilt–Rotate (TTR) mechanism, which enables collective alignment of the DUs to the respective MMA nodes during the commissioning phase (or later if needed). Northrop Grumman Innovation Systems (NGIS, formerly Orbital-ATK) provides the boom, its canister, and the TTR, under contract to Ball Aerospace, which is also responsible for other optical-bench components—including the thermal sock, electrical harnesses, and heaters for the boom canister and the TTR mechanism.

3. MIRROR MODULE ASSEMBLIES

In addition to managing the IXPE Project, NASA Marshall Space Flight Center (MSFC) is responsible for providing the four MMAs—three flight units and one spare—for the IXPE observatory. As was the case for MSFC-provided x-ray mirror assemblies for previous missions—the High-Energy Replicated Optics[8] (HERO) balloon-borne program, the Focusing Optics X-ray Solar Imager[9] (FOXSI) rocket-borne program, and the Astronomical Röntgen Telescope[10] (ART) aboard the Spectrum Röntgen Gamma (SRG) satellite—MSFC is performing most of the MMA activities in-house. These include specification (§3.1), mirror fabrication (§3.2), design (§3.3), alignment and assembly (§3.4), environmental testing (§3.5), and x-ray calibration (§3.6). Nagoya University is contributing the thermal shields on each end of the MMAs.

3.1. MMA specification

Figure 2 summarizes the configuration and performance specifications of the IXPE mirror module assemblies. Each of the 3 flight MMAs (plus 1 spare MMA) contains 24 nested nickel–cobalt shells, each of which includes the primary and secondary grazing-incidence mirror surfaces to achieve a 4001-mm focal length. As the x-ray optical properties of nickel are nearly ideal for IXPE's 2–8-keV band, there is no need for a separate optical coating on the mirrors.

Property	Value
Number of mirror modules	3
Mirror shells per module	24
Focal length	4.00 m
Total shell length	600 mm
Inner, outer shell diameter	162, 272 mm
Inner, outer shell thickness	178, 254 µm
Shell material	Nickel cobalt alloy
X-ray optical coating	None (bare Ni–Co)
Effective area per module	183 cm^2 (2.3 keV) > 210 cm^2 (3-6 keV)
Angular resolution	≤ 25 arcsec HPD
Detector limited FOV	12.9 arcmin
Mass (3 assemblies)	95 kg w/ contingency

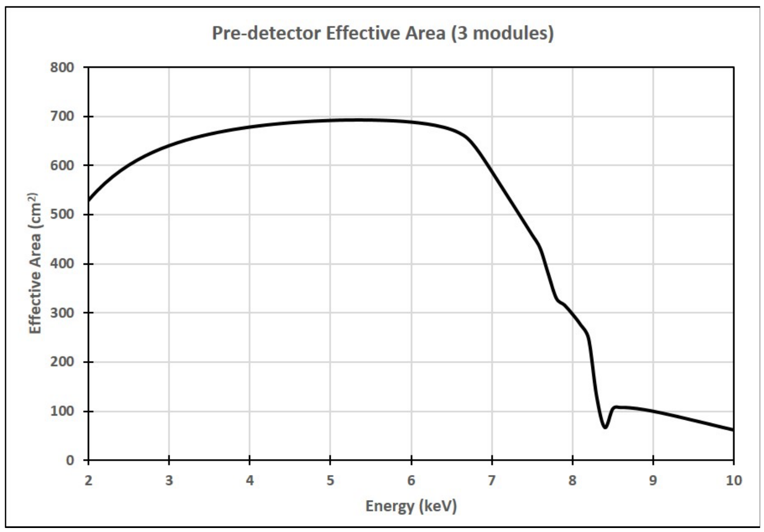

Figure 2. Configuration and performance specification of the IXPE Mirror Module Assemblies. Left panel tabulates various design and performance parameters. Right panel displays the expected effective area of 3 MMA optics, including attenuation by the thermal shields but not the efficiency of the detectors.

The principal optical-performance requirements on the MMAs are the effective area (A_{MMA}) and the half-power diameter ($\mathrm{HPD_{MMA}}$). Current best estimates of A_{MMA} and of $\mathrm{HPD_{MMA}}$ support the level-1 requirements on polarization sensitivity and on imaging resolution, respectively.

3.2. Mirror fabrication

The IXPE MMAs utilize electroformed nickel–cobalt shells, replicated from precision machined and polished metal mandrels. Electroformed-nickel replication (ENR) is a relatively low-cost technology for producing x-ray optics with moderate angular resolution (15"–30" half-power diameter, HPD). It is particularly cost effective for producing arrays of x-ray telescopes of the same optical design, for which several shells are replicated from each mandrel. In addition to the MSFC-produced ENR x-ray optics for HERO, FOXSI, and SRG ART, ENR x-ray optics were used for BeppoSAX, XMM-Newton, Swift X-Ray Telescope (XRT), and SRG eROSITA.

Figure 3 illustrates the process for producing ENR x-ray mirror shells. The steps proceed as follows: (a) machine a near-net-shape aluminum mandrel; (b) electroless plate nickel phosphorous onto the aluminum mandrel; (c) precision figure the nickel–phosphorous plated mandrel using single-point diamond turning (or other technique); (d) precision polish the figured mandrel to achieve a low-microroughness surface; (e) passivate the surface and electroform a shell in a nickel–

cobalt bath; and (f) separate the shell from the mandrel in a chilled-water bath and clean the mirror shell. Not shown in the figure are precision metrology measurements during figuring and polishing of the mandrel, which are essential in ensuring that the x-ray mirrors will support the angular-resolution requirements.

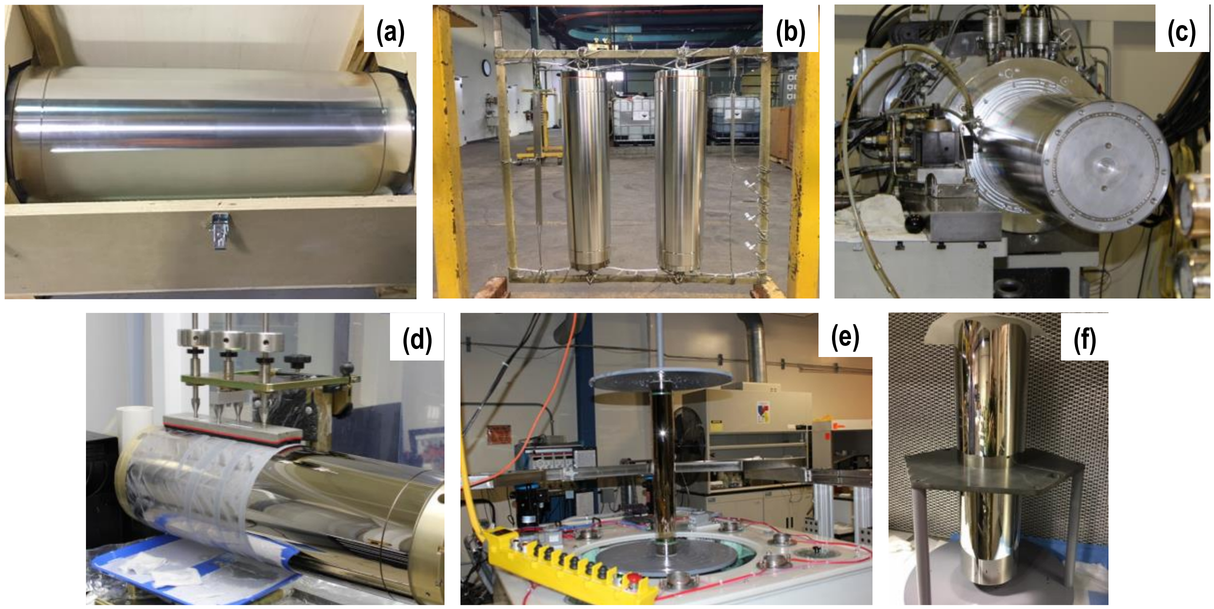

Figure 3. Mirror-shell production process.

The IXPE specification requires precision figuring and polishing of 24 mandrels in the size range listed in the table of Figure 2. These are the most time-consuming and, hence, costly steps in the mirror-shell production. The electroforming step itself is rather quick (about a day) and low-cost. Typically, several mirror shells can be electroformed from each mandrel with minimal refreshing of the surface. The IXPE specification calls for at least 4 mirror shells to be electroformed off each mandrel, for the 3 flight and one spare MMAs.

3.3. MMA design

Figure 4 displays the mechanical design of an MMA, shown with the front end down—its orientation during alignment and assembly (§3.4). In order of assembly, the principal components of the MMA are the front spider, central support tube, mirror shells (inner to outer), rear spider, outer housing, and thermal shields.

The front spider is the primary structural element of the design, through which the MMA will mount to the MMSS (§2.1) during Payload integration at Ball. The central support tube serves as an alignment reference and support structure for components at the rear end of the MMA. Each of the nine spokes of the front spider has a precisely fabricated and positioned comb glued to it. During MMA alignment and assembly, each mirror shell is inserted and glued into the corresponding slot between the tines of each comb, thus attaching the mirror shells to the spokes of the front spider.

The rear spider has 18 spokes, each with a metal comb. After all 24 shells have been glued to the front spider, the rear spider is attached to central support tube and its metal combs aligned such that each mirror shell floats within the corresponding slot between the tines of the rear-spider combs. Unlike the front-spider combs, which hold the mirror shells, the rear-spider combs merely limit excursions of the shells under launch loads to preclude shell-to-shell collisions.

The thermal shields, contributed by Nagoya University, limit radiative losses from the otherwise-open ends of the MMA and are an important part of the thermal design. Heaters and multi-layer insulation (MLI), provided by Ball Aerospace, are the other important components of the MMA thermal design. The thermal design supports thermal specifications, derived from finite-element analysis (FEA) and subsequent ray-trace simulations, to ensure that the half-power diameter (HPD) of the MMA image satisfies the IXPE imaging requirements (see table of Figure 2). As one might expect, the analyses show that the HPD is most sensitive to diametric temperature gradients, with less sensitivity to axial gradients and average temperature.

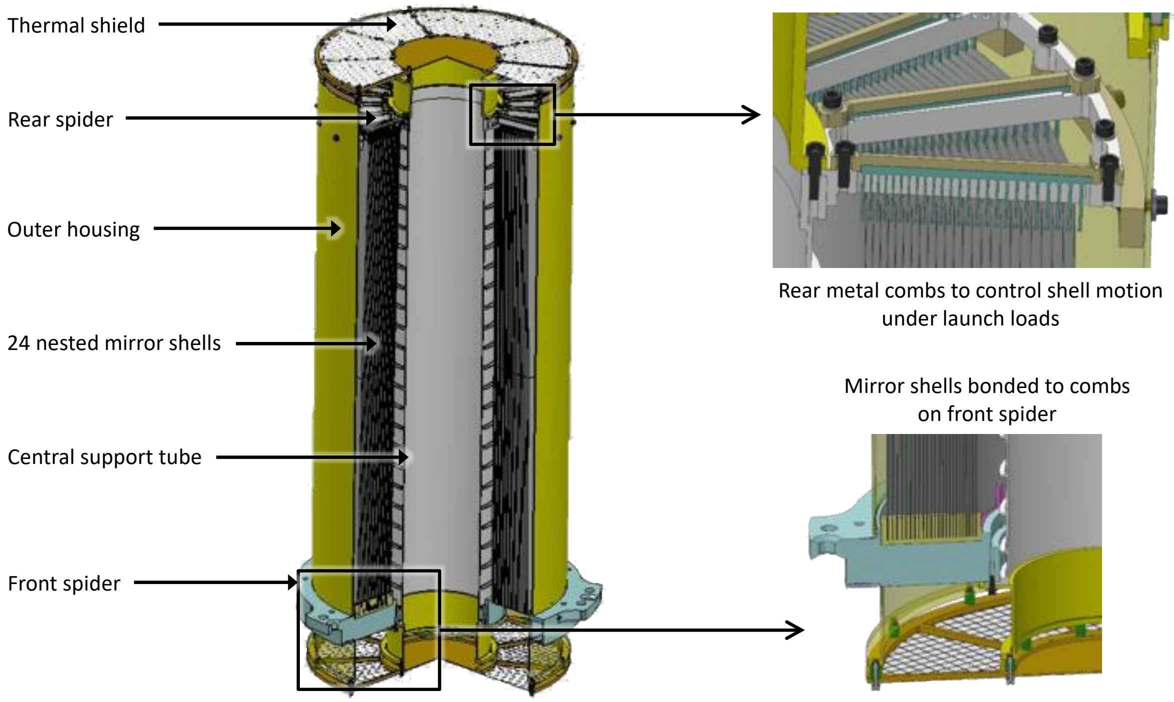

Figure 4. Mirror-module mechanical design, shown with the front end down. Left panel identifies the principal components of the design. The insets display the interface of the mirror shells with the rear spider (top) and with the front spider (bottom).

3.4. Alignment and assembly

Figure 5 shows the design (left panel) of an MMA alignment and assembly station and the graphical interface (right panel) for software-controlled optimization of the alignment of each shell. To allow parallel production of MMAs, there are 4 alignment and assembly stations, located in an ISO-7 (Class-10k) cleanroom to help satisfy cleanliness requirements for the x-ray optics.

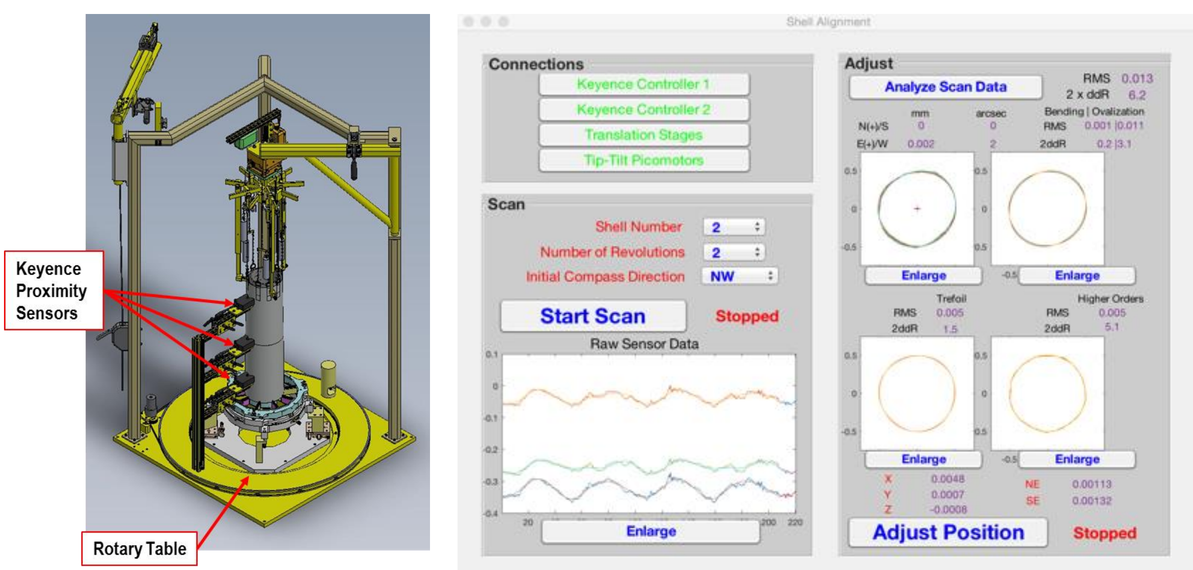

Figure 5. Alignment and assembly of mirror modules. Left panel is a schematic representation of an MMA alignment and assembly station. Right panel shows a display window for the software used to optimize alignment of a mirror shell.

Prior to installation into the MMA alignment and assembly station, a precision comb is accurately positioned and glued into a pocket in each of the nine spokes of the front spider (§3.3). In addition, the central support tube is aligned and attached to the front spider. After the spider–tube structure is installed front-end-down (Figure 5 left) and aligned to the station, installation of the 24 mirror shells begins, starting with the innermost shell and working outward.

The assembly system holds each successive shell by hanging it via a set of 9 support wires: 3 wires can be adjusted by piezo actuators and the other 6 serve as tuned-mass off-loaders. The rotary table and proximity sensors rotate together under computer control, as the sensors measure radial displacements of the external surface of the mirror shell. Software acquires the displacement data as a function of rotation angle and fits those data to various curves, calculating parameters (shell center, tilt, circularity) that aid in the alignment process. Custom software analyzes these calculated parameters and adjusts the 3 non-offloaded hanging points to converge to the required centering and tilt. This computer-controlled process typically converges in about 20 minutes. Once convergence is achieved, the operator injects epoxy into the front-spider comb slots and the assembly is left to cure overnight.

The aforesaid process repeats for each of the 24 mirror shells. After all 24 shells have been aligned and installed, the rear spider with an aligned metal comb in each of its 18 spokes is installed onto the central support tube such that all shells float within the rear-spider comb slots. The thermal shields are installed when needed, after assembly of the MMA itself.

3.5. Environmental testing

Prior to x-ray calibration (§3.6), each MMA with thermal shields will undergo environmental testing at MSFC's Environmental Test Facility. The environmental tests include vibration and acoustic acceptance testing consistent with the levels expected for a Falcon-9 launch, as well as thermal cycling.

The designs (§3.3), of the MMA and of the thermal shield have been refined over the past year, based upon results of vibration testing of the MMA engineering unit and of acoustic testing of thermal-shield engineering units. The current designs are more robust and accommodate the Falcon-9 launch environment.

3.6. X-ray calibration

An extensive x-ray calibration campaign has been planned.[11] The campaign comprises calibration of the detector units (DUs, §2.2) at INAF IAPS, of the MMAs at MSFC, and of at least one Telescope (MMA and DU combined) at MSFC.

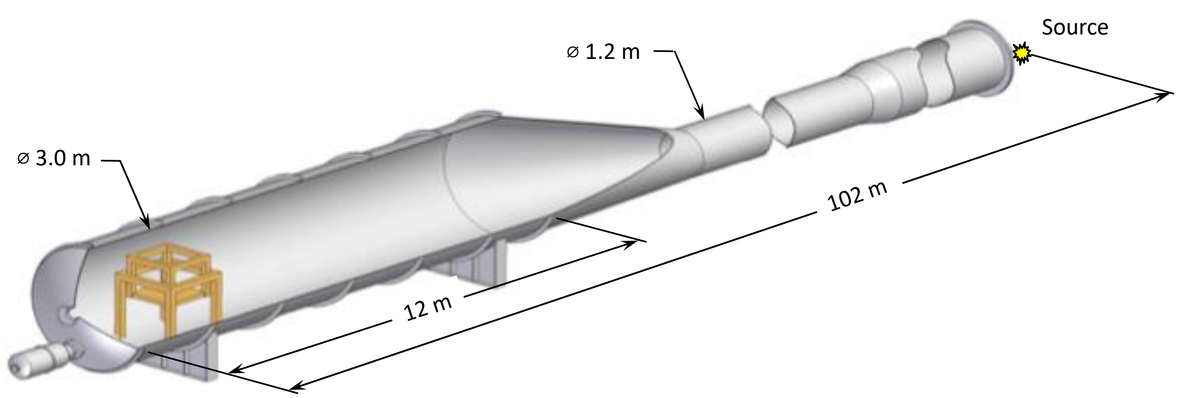

Figure 6. X-ray testing and calibration at MSFC's 100-m x-ray test facility ("Stray-Light Test Facility").

Using its 100-m x-ray test facility (Figure 6), MSFC will calibrate each MMA using GSE detectors and sources at several x-ray energies, measuring MMA effective area and point spread function on axis and at several off-axis angles, ghost (non-imaged) x rays, and focal length. While calibration of a Telescope (MMA+DU) can be synthesized from separate MMA and DU calibrations, at least one MMA and DU will be calibrated together to validate the synthesized response. This validation will measure the Telescope point spread function and effective area for a subset of energies and off-axis angles used for the analogous MMA measurements with GSE detectors. In addition, it will use custom polarized sources to measure polarization-related properties—modulation factor and spurious polarization—for the Telescope. These should be practically identical to those for the DU alone, as grazing-incidence reflectance is nearly independent of polarization.

4. MMA STATUS

IXPE successfully completed its Mission Critical Design Review (CDR) in 2019 June and will hold its Ground System CDR in 2019 November. Alignment and assembly of the 3 flight MMAs is underway at MSFC, with x-ray calibration of the 3 flight units projected to occur in 2020 March, prior to shipment to Ball Aerospace for Payload integration in 2020 Spring. The expected IXPE launch date is in 2021 Spring.

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REFERENCES

[1] Weisskopf, M. C., Ramsey, B., O'Dell, S., Tennant, A., Elsner, R., Soffitta, P., Bellazzini, R., Costa, E., Kolodziejczak, J., Kaspi, V., Muleri, F., Marshall, H., Matt, G., & Romani, R., "The Imaging X-ray Polarimetry Explorer (IXPE)," SPIE 9905, 17 10pp (2016).

[2] Soffitta, P., "IXPE the Imaging X-ray Polarimetry Explorer," SPIE 10397, 0I 9pp (2017).

[3] O'Dell, S. L., Baldini, L., Bellazzini, R., Costa, E., Elsner, R. F., Kaspi, V. M., Kolodziejczak, J. J., Latronico, L., Marshall, H. L., Matt, G., Mulieri, F., Ramsey, B. D., Romani, R. W., Soffitta, P., Tennant, A. F., Weisskopf, M. C., Allen, D. Z., Amici, F., Antoniak, S., Attinà, P., Bachetti, M., Barbanera, M., Baumgartner, W. H., Bladt, J., Bongiorno, S. D., Borotto, F., Brooks, T., Bussinger, S., Bygott, H. K., Cavazzuti, E., Ceccanti, M., Citraro, S., Deininger, W. D., Del Monte, E., Dietz, K. L., Di Lalla, N., Di Persio, G., Donnarumma, I., Erickson, J., Evangelista, Y., Fabiani, S., Ferrazzoli, R., Foster, M., Giusti, M., Gunji, S., Guy, L., Johnson, S., Kalinowski, W., Kelley, A. R., Kilaru, K., Lefevre, C., Maldera, S., Manfreda, A., Marengo, M., Masciarelli, J., McEachen, M., Mereu, P., Minuti, M., Mitchell, M. A., Mitchell, S., Mitsuishi, I., Morbidini, A., Mosti, F., Nasimi, H., Negri, B., Orsini, L., Osborne, D., Pavelitz, S. D., Pentz, C., Perri, M., Pesce-Rollins, M., Peterson, C., Piazzolla, R., Pieraccini, S., Pilia, M., Pinchera, M., Puccetti, S., Ranganathan, J., Read, T., Rubini, A., Santoli, F., Sarra, P., Schindhelm, S., Sciortino, A., Seckar, C., Sgrò, C., Smith, B. T., Speegle, C. O., Tamagawa, T., Tardiola, M., Tobia, A., Tortosa, A., Trois, A., Weddendorf, B., Wedmore, J., & Zanetti, F., "The Imaging X-ray Polarimetry Explorer (IXPE): technical overview," SPIE 10699, 1X 14pp (2018).

[4] O'Dell, S. L., Attinà, P., Baldini, L., Barbanera, M., Baumgartner, W. H., Bellazzini, R., Bladt, J., Bongiorno, S. D., Brez, A., Cavazzuti, E., Citraro, S., Costa, E., Deininger, W. D., Del Monte, E., Dietz, K. L., Di Lalla, N., Donnarumma, I., Elsner, R. F., Fabiani, S., Ferrazzoli, R., Guy, L., Kalinowski, W., Kaspi, V. M., Kelley, A. R., Kolodziejczak, J. J., Latronico, L., Lefevre, C., Lucchesi, L., Manfreda, A., Marshall, H. L., Masciarelli, J., Matt, G., Minuti, M., Mulieri, F., Nasimi, H., Nuti, A., Orsini, L., Osborne, D., Perri, M., Pesce-Rollins, M., Peterson, C., Pinchera, M., Puccetti, S., Ramsey, B. D., Ratheesh, A., Romani, R. W., Santoli, F., Sciortino, A., Sgrò, C., Smith, B. T., Spandre, G., Soffitta, P., Tennant, A. F., Tobia, A., Trois, A., Wedmore, J., Weisskopf, M. C., Xie, F., Zanetti, F., Alexander, ., Allen, D. Z., Amici, F., Antoniak, S., Bonino, R., Borotto, F., Breeding, S., Brienza, D., Bygott, H. K., Caporale, C., Cardelli, C., Ceccanti, M., Centrone, M., Di Persio, G., Evangelista, Y., Ferrie, M., Footdale, J., Forsyth, B., Foster, M., Gunji, S., Gurnee, E., Hibbard, G., Johnson, S., Kelly, E., Kilaru, K., La Monaca, F., Le Roy, S., Loffredo, P., Magazzu, G., Marengo, M., Marrocchesi, A., Massaro, F., McCracken, J., McEachen, M., Mereu, P., Mitchell, S., Mitsuishi, I., Morbidini, A., Mosti, F., Negro, M., Oppedisano, C., Pacheco. R., Paggi, A., Pavelitz, S. D., Pentz, C., Piazzolla, R., Porter, B., Profeti, A., Ranganathan, J., Rankin, J., Root, N., Rubini, A., Ruswick, S., Sanchez, J., Scalise, E., Schindhelm, S., Speegle, C. O., Tamagawa, T., Tardiola, M., Walden, A., Weddendorf, B., & Welch, D., "The Imaging X-ray Polarimetry Explorer (IXPE): technical overview II," SPIE 11118, 0V 14pp (2019).

[5] Ramsey, B. D., “Optics for the Imaging X-ray Polarimetry Explorer,” SPIE 10399, 07 10pp (2017).

[6] Nasimi, H., “Overview of the detector and its readout on board the Imaging X-ray Polarimetry Explorer,” SPIE 10699, 5D 8 pp (2018).

[7] Sgrò, C., “The gas pixel detector on board the IXPE mission,” SPIE 10397, 0F 7pp (2017).

[8] Ramsey, B. D., Alexander, C. D., Apple, J. A., Benson, C. M., Dietz, K. L., Elsner, R. F., Engelhaupt, D. E., Ghosh, K., Kolodziejczak, J. J., O'Dell, S. L., Speegle, C. O., Swartz, D. A., & Weisskopf, M. C., “HERO: program status and first images from a balloon-borne focusing hard x-ray telescope,” SPIE 4496, 140-145 (2002).

[9] Glesener, L., Krucker, S., Christe, S., Ishikawa, S.-N., Buitrago-Casas, J. C., Ramsey, B., Gubarev, M., Takahashi, T., Watanabe, S., Takeda, S., Courtade, S., Turin, P., McBride, S., Shourt, V., Hoberman, J., Foster, N., & Vievering, J., “The FOXSI solar sounding rocket campaigns,” SPIE 9905, 0E 12pp (2016).

[10] Gubarev, M., Ramsey, B., Elsner, R., O’Dell, S., Kolodziejczak, J., McCracken, J., Zavlin, V., Swartz, D., Kilaru, K., Atkins, C., Pavlinsky, M., Tkachenko, A., & Lapshov, I., “ART-XC/SRG: status of the x-ray optics development,” SPIE 9144, 1V 6pp (2014).

[11] Muleri, F., Baldini, L., Baumgartner, W., Evangelista, Y., Fabiani, S., Kolodziejczak, J., Latronico, L., Lefevre, C., O'Dell, S. L., Ramsey, B., Sgrò, C., Soffitta, P., Tennant, A., & Weisskopf, M. C., “Calibrating the IXPE observatory from ground to space,” SPIE 10397, 0G 8pp (2017).