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Calibrating the IXPE observatory from ground to space

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ABSTRACT

The Imaging X-ray Polarimetry Explorer (IXPE) will be the next SMEX mission launched by NASA in 2021 in collaboration with the Italian Space Agency (ASI). IXPE will perform groundbreaking measurements of imaging polarization in X-rays for a number of different classes of sources with three identical telescopes, finally (re)opening a window in the high energy Universe after more than 40 years since the first pioneering results. The unprecedented sensitivity of IXPE to polarization poses peculiar requirements on the payload calibration, e.g. the use of polarized and completely unpolarized radiation, both on ground and in orbit, and can not rely on a systematic comparison with results obtained by previous observatories. In this paper, we will present the IXPE calibration plan, describing both calibrations which will be performed on the detectors at INAF-IAPS in Rome (Italy) and the calibration on the mirror and detector assemblies which will be carried out at Marshall Space Flight Center in Huntsville, Alabama. On orbit calibrations, performed with calibrations sources mounted on a filter wheel and placed in front of each detector when necessary, will be presented as well.

Keywords: Imaging X-ray Polarimetry Explorer, calibration, on-ground, in-flight

1. INTRODUCTION

The Imaging X-ray Polarimetry Explorer (IXPE, see Soffitta et al. in this same volume[1]) will be the first observatory sensitive to X-ray polarization to be launched since the 1970s. The novelty of this kind of measurements is the first reason of interest in the mission, and at the same time poses new challenges for the precise calibration of the instrumentation that will be used on-orbit. On the one hand, only one source - the Crab Nebula - is known to be polarized[2] and can then be used for calibrating IXPE with respect to previous experiments. On the other, one of the driving scientific requirements of the mission is the capability to detect X-ray polarization as low as 1%, which requires to calibrate the instrumental response to lower than this level with appropriate calibration sources.

2. IXPE PAYLOAD

IXPE payload is dedicated specifically to X-ray polarimetry and it is composed of three identical telescopes. Each telescope is the combination of a grazing-incidence mirror (Mirror Module Assembly, MMA) and of a Detector Unit (DU) hosting an X-ray imaging photoelectric polarimeter based on the Gas Pixel Detector design (GPD[3–5]). The operative energy range of the GPD is 2-8 keV; in such energy range, the GPD can image the track of the photoelectron produced in a gas cell, deriving the energy of the incident photon, its time of arrival, the position of absorption on the focal plane and, on a statistical base on the entire sample, the linear polarization degree and angle (see Sgró et al. in this same volume[6]). A picture of IXPE spacecraft after on-orbit deployment in shown in Figure 1.

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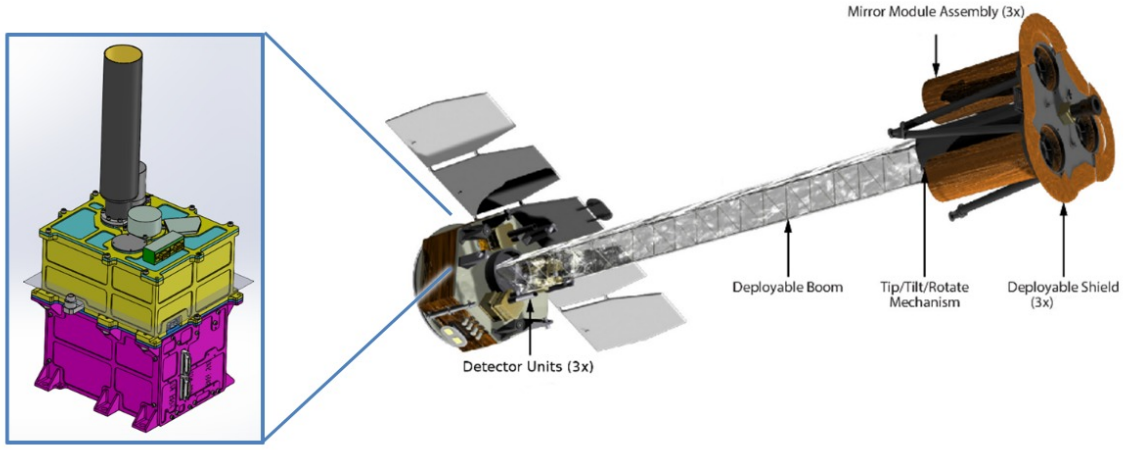


Figure 1. IXPE satellite after on-orbit deployment. A zoom on the DU is on the left.

3. IXPE CALIBRATION

IXPE calibration will rely primarily on an extensive ground campaign with well-characterized laboratory sources. The approach will be modular; each DU and MMA will be first calibrated alone and then each pair will be calibrated during "Telescope" calibrations. Three models and one spare for both the DU and the MMA will be calibrated, also with telescope calibrations. On-orbit, calibration sources in the DU will be used to monitor critical instrument characteristics, e.g., the response to both polarized and unpolarized radiation and the energy resolution, which are however anticipated to be very stable over a period of time comparable to IXPE lifetime.[7] Observation of celestial sources, e.g. the Crab nebula and/or other sources with stable and well-characterized polarization signature which may be identified during IXPE observations, will be used to cross-check results from on-board calibration sources.

The knowledge of polarization degree and angle are not standard requirements for commercial X-ray sources, so we are developing custom X-ray sources to calibrate the IXPE observatory. Bragg diffraction at nearly 45 degrees provides an effective technique for generating polarized X-rays in the IXPE energy range and it has been extensively used in the past.[8] Unpolarized radiation will be generated with ^{55}Fe radioactive isotope, which has a very low polarization but provides calibration only at one energy, and with special arrangements of standard X-ray tubes. A set-up under evaluation is the rotation of X-ray tubes around the beam direction to remove polarization due to continuum bremsstrahlung radiation, which is intrinsically polarized, or to not axisymmetric internal scattering in the source. An alternative set-up which has been already used for the calibration of GPD prototypes and which does not require movements in the source assembly is the use of head-on X-ray tubes. In this case, X-rays are emitted through the anode, parallel to accelerated electrons, and therefore the net polarization is low for symmetry reasons.

3.1 DU calibration

DU calibration on-ground will be carried out at INAF-IAPS in Italy and it will comprise of a sequence of measurements already routinely performed on GPD prototypes. In particular, DU calibrations will be dedicated to:

- measure and map the GPD modulation factor, that is, the amplitude of the response to completely polarized radiation;
- measure and map the GPD energy resolution;
- measure and map the GPD spatial resolution;

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- measure the GPD quantum efficiency;
- map the GPD gain uniformity.

Calibration sources and set-up for IXPE DU are directly derived with minor adjustments from the facility that has been used for GPD calibration for nearly ten years.[9] Polarized radiation is generated by diffracting at 45 deg the radiation produced by commercial X-ray tubes. The energies listed in Table 1, covering completely the IXPE energy range, are already available at INAF-IAPS by means of a suitable choice of X-ray tubes and diffracting crystals. The source design is being revised for including fiducial marks to measure the orientation of the diffracting crystal, and then of the diffracted beam, in the GPD frame of reference. On the one hand, this will provide the absolute measurement of the angle of polarization of incident radiation, which will be used during the calibration of the relation between the expected and measured values of the polarization angle. On the other, the knowledge of beam direction will allow us to adjust GPD orientation which has to be orthogonal to obtain a purely cosinusoidal response for polarized radiation and a statistically flat one for unpolarized photons.[10] Alignment procedure will comprise two steps: the first will be the measurement of the relative orientation of the diffracting crystal and the GPD through the respective fiducial marks; the second step will be the correction of the measured misalignment by means of a tip-tilt stage. The procedure will be repeated any time the crystal is replaced.

Energy (keV)	Crystal	X-ray tube
1.7	Ammonium dihydrogen phosphate - ADP	Titanium, 50 W
2.0	Pentaerythritol - PET	Titanium, 50 W
2.6	Graphite	Titanium, 50 W
3.7	Aluminum	Calcium, 0.2 W
4.5	Calcium fluorite	Titanium, 50 W
5.2	Graphite, II order of diffraction	Titanium, 50 W
6.4	Silicon	Iron, 50 W
8.0	Germanium	Copper, 2.0 W
9.7	Lithium fluoride	Gold, 25 W

Table 1. List of energies which will be used for DU calibration, with indication of used X-ray tube and diffracting crystal.

Unpolarized radiation will be generated either with ^{55}Fe radioactive sources, whose residual polarization is much lower than 1%, or with head-on X-ray tubes. Three X-ray tubes of this kind are available at INAF-IAPS, with Calcium, Copper and Tungsten anodes; for the first we detect a polarization lower than 0.5% on the Calcium K fluorescence (see Figure 2), which makes it ideal for IXPE DU calibration. Diaphragms with diameter from 25 μm can be used to control the beam spot for the different kinds of measurements.

A sketch of the set-up for DU calibrations is shown in Figure 3. Position of the beam will be controlled with micrometric stages controlled by a PC, to carry out automatically the sequence of measurements required to map the GPD response over all its 15×15 mm^2 sensitive area. Beam rotation around the incident direction will be controlled as well to construct the relation between the expected and measured angle of polarization. Calibrations on flight units will be carried out in a clean room of class <100,000 (ISO8), which is being refurbished at INAF-IAPS. A removable enclosure not shown in Figure 3 will enclose all the set-up to assure the shielding of X-rays. All equipment will be connected to a local uninterrupted power supply that will allow to turn off automatically the DU and the calibration source in safe condition in case of power failure.

3.2 MMA and Telescope calibration

Calibration of Mirror Module Assembly and of IXPE telescopes will be carried out at NASA MSFC Stray Light Test Facility (SLTF) in Huntsville, Alabama. This facility has been extensively used for calibration of X-ray mirrors, e.g. ART-XC on-board Spectrum-Roentgen-Gamma (SRG) mission,[11] and IXPE calibration does not require any special additional need. The facility features a long beam-line, about 100 m depending on the actual instrument set-up, a main instrument chamber which is 12 m long and 3 m in diameter, and a smaller extension to operate small telescopes (or just the focal plane detector) without entering the main chamber (see Figure 4).

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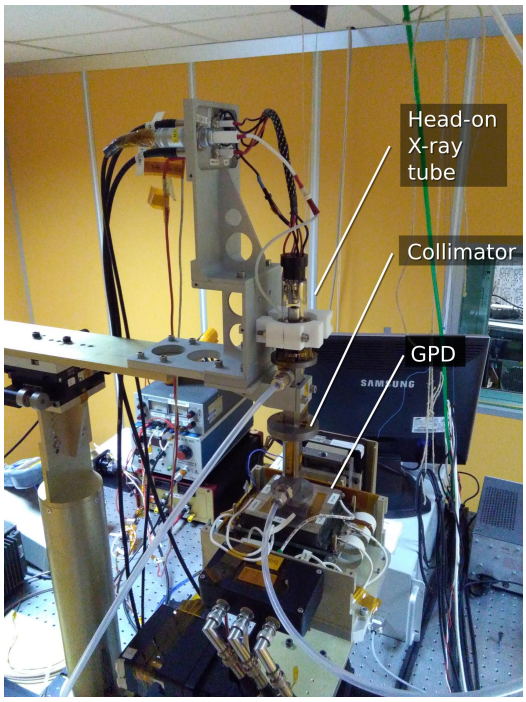


Figure 2. Set-up with head-on X-ray tube for the generation of unpolarized radiation.

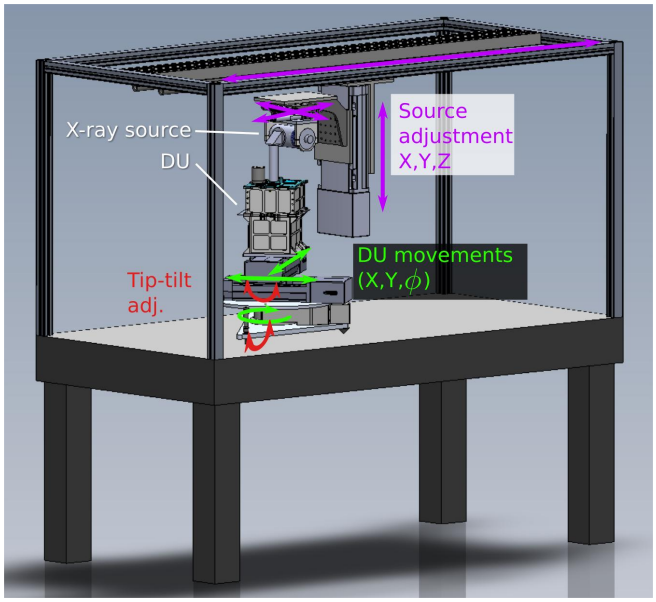


Figure 3. Sketch of the calibration equipment for DU calibration.

Existing standard sources will be used for telescope engineering model and mirror shell verification, testing and calibration dry-run. X-ray tubes with Titanium, Iron and Copper anodes, whose K fluorescence lines are respectively at 4.5, 6.4 and 8.0 keV, are already available and the procurement of further X-ray tubes with Rhodium and Aluminum anodes is under evaluation. For calibration of IXPE telescopes, the design of completely unpolarized sources, based on the periodic rotation of any of the available X-ray tubes, and polarized sources, based on Bragg diffraction, are being investigated. Commercial CCDs will be used as focal plane detector during

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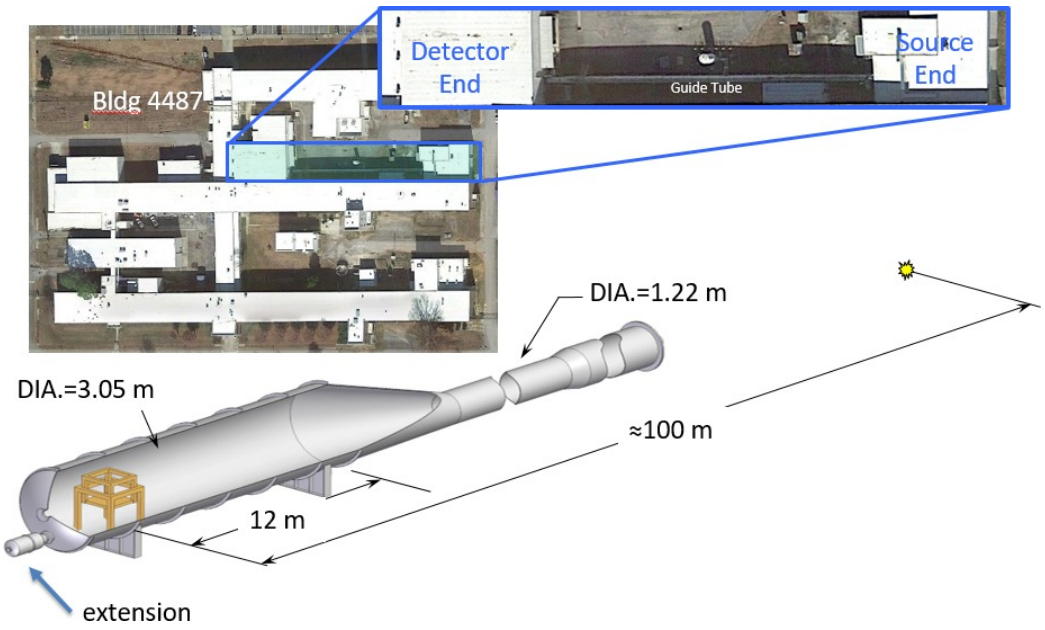


Figure 4. Sketch of the MSFC Stray Light Test Facility in Huntsville, Alabama.

MMA calibrations and for diagnostic purposes. Slit for spot characterization, filters to limit flux and maintain spectral purity and vacuum-compatible stages to move the mirror and the focal plane detector are available as well.

MMA calibrations will be performed with commercial CCDs to measure the following:

- the MMA focal length;
- the effective area to 5%, on- and off-axis at several energies, nominally Al-K, Ti-K, Fe-K and Cu-K;
- the MMA Point Spread Function to better than 2% at the same energies and off-axis

Telescope calibrations, during which flight DUs will be used together with the corresponding MMA, will be dedicated to measure the effective area and angular resolution as a function of energy. The measurement of modulation factor on- and off-axis including the contribution due to mirror focusing will be done in case the polarized source is available; as a backup, the effect will be evaluated during DU calibrations by inclining the beam of the appropriate angle and rotating the DU around its orthogonal axis.

3.3 On-orbit calibration

Periodic on-orbit calibration of the DU will be possible thanks to calibration sources hosted in each DU and placed in front of each GPD by means of a Filter and Calibration Wheel (FCW). Each FCW has 7 positions:

1. an "open" position for normal observations. In this position no filter is put in front of the detector and the clearance is such that there is no obstruction in the telescope field of view.
2. a "closed" position, for measuring the GPD internal background and for GPD protection during, e.g., launch. In this position a filter which is completely opaque to X-rays in the IXPE energy range is placed in front of the GPD.
3. a "gray" filter position. This filter will be used to observe exceptionally bright sources, with a flux higher than about 2 Crab. Its thickness and material are chosen so that the counting rate on the detector is reduced of a factor a few.

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4. a polarized calibration source, based on Bragg diffraction at nearly 45 deg and on a design already presented.[8] The source will be able to generate 2.6 and 5.9 keV photons with a high and precisely known polarization degree, thanks to the precise knowledge of the energy of diffracted photons, to monitor modulation factor, energy resolution and gain. The angle of polarization in the GPD frame of reference will also be precisely known, through the knowledge of crystals orientation with respect to FCW fiducial marks, which will be referred to those on the GPD on-ground, and to the strict requirement on the FCW positioning (better than 20 arcmin).

5. an unpolarized collimated calibration source based on a ^{55}Fe radioactive source and on a pinhole to generate a spot of a few mm^2 on the GPD. The source will be used to monitor the detector response to unpolarized radiation.

6. a ^{55}Fe calibration source that fully illuminates the GPD sensitive area at 5.9 keV (full-illumination source #1). This is used for mapping GPD gain disuniformities.[7]

7. a source of Copper X-ray fluorescence, extracted by a ^{109}Cd radioactive source, which fully illuminates the GPD sensitive area at 8.0 keV to map the GPD gain and its disuniformities at a second energy (full-illumination source #2).

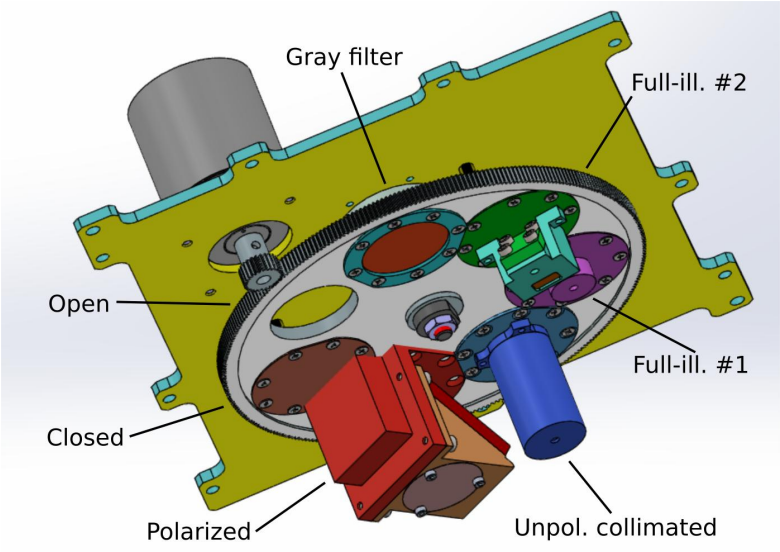


Figure 5. Preliminary design of the Filter and Calibration Wheel on-board IXPE.

A preliminary design of the Filter and Calibration Wheel and of the four calibration sources are reported in Figure 5 and Figure 6, respectively. Tubular shields, not shown in the figures, will allow X-ray photons for each source to arrive on the GPD only when the source is placed in front of it. Radioactive sources will remain accessible and replaceable after DU integration through a dedicated aperture on the DU lid. This will facilitate on-ground handling, because radioactive material will be removed during unit transportation or safety-critical tests. Moreover, the capability to insert new radioactive sources as late as possible in the spacecraft integration flow will limit the amount of radioactive material necessary to have a reasonable flux from calibration sources during all IXPE lifetime.

4. CONCLUSIONS

The calibration of IXPE observatory will be based mainly on an extensive ground campaign. It will be carried out with a modular approach, starting first from the separate characterization of the Mirror Module Assembly and of the Detector Unit, and then by combining these two components in the Telescope calibrations. On-ground

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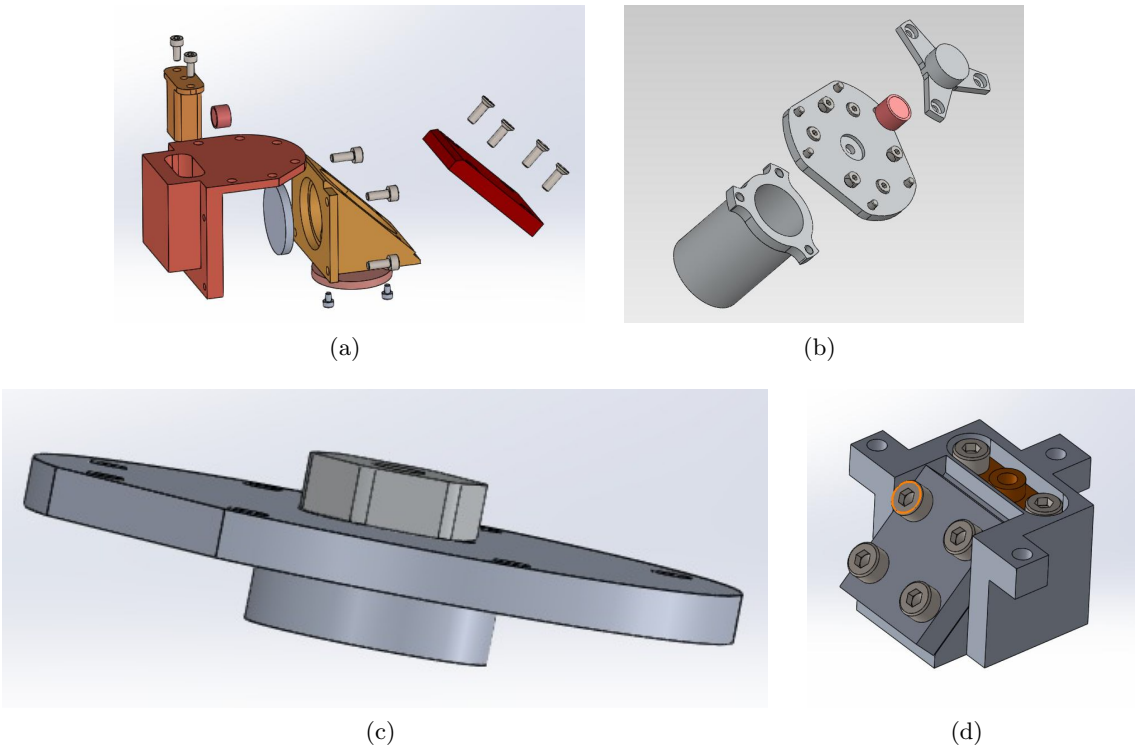


Figure 6. Design of the four calibration sources hosted in the FCW. From top-left to bottom-right: polarized sources (**a**), unpolarized collimated sources (**b**), first full-illumination source at 5.9 keV (**c**), second full-illumination source at 8.0 keV (**d**).

payload calibrations will allow to precisely characterize the observatory response to polarization and its spectral and imaging capabilities. Calibration on-orbit will be possible thanks to sources included in the payload, which will be placed in front of the detector when necessary by rotating a filter and calibration wheel. These will enable monitoring the essential characteristics of the detector, that is, its response to polarized and unpolarized radiation and its energy resolution, which are however already anticipated to be very stable over a period of time comparable to IXPE lifetime.

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