

## The Telescope Calibration of the Imaging X-ray Polarimetry Explorer

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### Abstract

Fifty years after the very first sounding rocket measurement of cosmic X-ray polarization, the Imaging X-ray Polarimetry Explorer (IXPE) mission has effectively opened a new window into the X-ray sky. Prior to launch of IXPE, an extensive calibration campaign was carried out to fully characterize the response of this new type of instrument. Specifically, the polarization-sensitive detectors were intensively calibrated in Italy, where they were developed and built. The X-ray optics, which collect and focus X rays onto the detectors, were built and calibrated in the U.S. A key question was whether the telescope (optics + detectors) calibrations could be synthesized from the individual component calibrations, avoiding time consuming and costly end-to-end calibrations for a flight program with a fixed schedule.

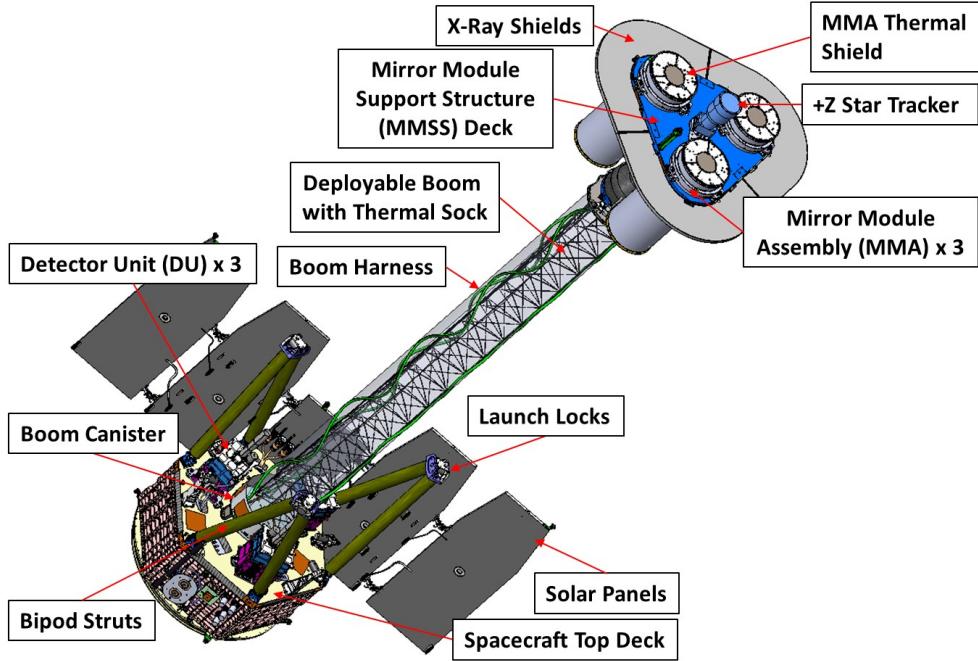
The data presented here are from a calibration of the flight spare telescope utilizing the flight spare detector and flight spare mirror assembly combined. These data show that the presence of the mirror module does not affect the polarization response of the detectors (within the required calibration accuracy) and that the angular resolution of the telescopes could be accurately determined. Thus, the original extensive stand-alone ground calibration data of all the flight detectors and all the flight optic can be utilized in full to derive the flight telescopes calibrations.

**Keywords:** Astrophysics, X-rays, Polarization, Optics, Detectors, Calibration

### 1. INTRODUCTION

Launched in late 2021, IXPE, the Imaging X-ray Polarimetry Explorer (IXPE, Figure 1) is a NASA small explorer mission that has opened a new window on the X-ray sky, 50 years since the first observations were made (Novick et al. 1972, 1978). The IXPE observatory, placed in a low-earth (600 km) equatorial orbit, consist of 3 identical telescopes each comprising an X-ray mirror module assembly (MMA) with a polarization-sensitive imaging X-ray detector unit (DU) at its focus. An extending boom, deployed on orbit, provides the necessary 4-m focal length and the payload sits atop a 3-axis stabilized spacecraft that provides for the payload command and control. IXPE is a collaboration between NASA and ASI, the Italian Space Agency. In the U.S., NASA's Marshall Space Flight Center (MSFC) is the lead Institution providing overall program management, system engineering, safety and mission assurance oversight, and science operations. It is also responsible for development of the mirror module assemblies and for providing MMA and Telescope calibrations. ASI is responsible for providing the instrument (Soffitta et al. 2021), composed of the polarization-sensitive imaging detectors (Baldini et al. 2021) and a detectors service unit, and the IXPE ground station situated near the equator in Malindi, Kenya. The IXPE mission in Italy is led by the Istituto di Astrofisica e Planetologia Spaziali - Istituto Nazionale di Astrofisica (INAF-IAPS), which designed and built the flight calibration sources (Ferrazzoli et al. 2020) and was responsible for the ground calibration of the flight detectors (Muleri et al. 2022; Di Marco et al. 2022). The detectors were designed and developed at the Istituto Nazionale di Fisica Nucleare (INFN) in Pisa. Detailed

descriptions of the IXPE program can be found in Weisskopf et al. (2022b) and Weisskopf et al. (2022a). The latter includes a discussion of IXPE science.



**Figure 1.** The Imaging X-ray Polarimetry Explorer with three polarization-sensitive Detector Units at the focus of three X-ray Mirror Module Assemblies.

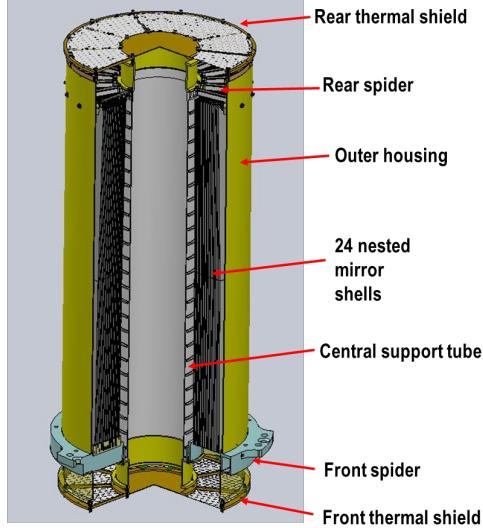
## 2. TELESCOPE DETAILS

### 2.1. Mirror Module Assembly

Each Mirror Module Assembly (MMA, Figure 2) consists of 24 concentrically-nested X-ray-mirror shells fabricated via an electroformed-nickel-replication process. Each shell contains both the primary and secondary (parabolic and hyperbolic) components of a Wolter-1-type optical configuration. The mirror shells are closely packed and quite thin, to meet a science-imposed effective area requirement while keeping the mass within launch requirements. The shells are held in place by a forward spider into which they are glued during shell alignment and assembly. A thin outer housing provides mechanical protection and thermal control via surface-mounted heaters. Completing the design is a pair of ultra-thin thermal shields, mounted each end, that together with the housing heaters permit active control of the MMA operating temperature while allowing X-rays in IXPE's operating band (2-8 keV) to enter and leave with high efficiency. Table 1 lists the MMA parameters. Full details of the IXPE MMA are given in Ramsey et al. (2022).

### 2.2. Detector Unit

The IXPE Detector Unit (DU) measures the energy, position, arrival time and polarization of each absorbed X-ray photon that was focused by the MMA. The heart of each DU is the Gas Pixel Detector (GPD, Figure 3), a small (15 mm x 15 mm) proportional counter with a special fill gas, Dimethyl-Ether (DME), and a fine pixel readout, via a custom Application Specific Integrated Circuit (ASIC), that allows the imaging of photoelectron-induced tracks produced when X rays photoelectrically interact with the fill medium (see Kaaret (2021) for a general description of the workings of photoelectric polarimeters). The initial direction of the photoelectron, the interaction point and the total charge in the track, provide the necessary information to determine the polarization, location and energy of the absorbed X-ray photon, respectively. X rays enter through a beryllium window (Figure 3) and interact with the DME in an absorption and drift region. The resultant photoelectron track is then drifted down through a Gas Electron Multiplier (GEM) where each charge in the track is amplified before being registered on a highly-pixelated anode plane. This anode plane is the front end of the custom ASIC which processes the event so that it can be sent to the ground for track reconstruction and subsequent analysis. This analysis, among other things, bins the data to determine



**Figure 2.** An IXPE Mirror Module Assembly.

**Table 1.** IXPE MMA Parameters.

Parameter	Value
Number of mirror modules	3
Number of shells per mirror module	24
Focal length	4 m
Total shell length	600 mm
Range of shell diameters	162–272 mm
Range of shell thicknesses	0.18–0.25 mm
Shell material	Electroformed nickel–cobalt alloy
Effective area per mirror module	166 cm <sup>2</sup> (@ 2.3 keV) > 175 cm <sup>2</sup> (3–6 keV)
Angular resolution (HPD)	≤ 28 arcsec
Field of view (detector limited)	12.9 arcmin square

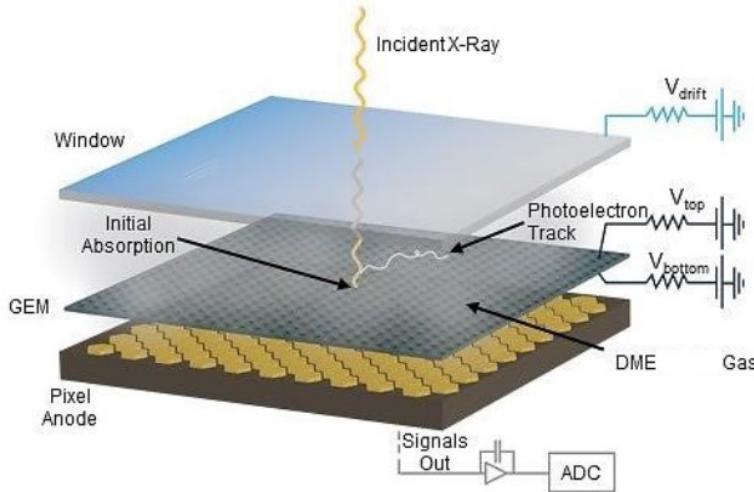
**Table 2.** Gas Pixel Detector parameters.

Parameter	Value
Sensitive area	15 × 15 mm (13 x 13 arcmin)
Fill gas and fill pressure	DME @ 0.8 atmosphere
Detector window	50-μm thick beryllium
Absorption and drift region depth	10 mm
Spatial resolution (FWHM)	≤ 123 μm (6.4 arcsec, 2 keV)
Energy resolution (FWHM)	0.57 keV @ 2 keV ( $\propto \sqrt{E}$ )
Useful energy range	2 - 8 keV

the polarization degree and polarization angle for each cosmic X-ray source observed. Parameters of the IXPE GPDs are given in Table 2; comprehensive descriptions of the Instrument and its GPD, can be found in (Soffitta et al. 2021) and (Baldini et al. 2021), respectively.

### 3. ON-GROUND TELESCOPE CALIBRATION

#### 3.1. Requirements



**Figure 3.** Schematic of the Gas Pixel Detector.

The sensitivity of a polarimeter is given by the equation:

$$MDP = \frac{429\%}{\mu} \times \frac{\sqrt{(R_s + R_b) \times t}}{R_s \times t} \quad (1)$$

where  $R_s$  is the source count rate (a product of the source flux, the mirror module effective area, and the detector quantum efficiency),  $R_b$  is the background rate,  $t$  is the observation time and  $\mu$  is the modulation factor which describes the response of the polarimeter to 100% polarized X rays. The sensitivity, MDP, is the minimum detectable degree of polarization that can be measured at the 99% confidence level. The parameters  $\mu$ ,  $R_s$  and  $R_b$  are all energy dependent. To accurately determine the sensitivity of the polarimeter, the effective area of the optics must be measured both on axis and for a variety of off-axis angles and azimuths, for a range of energies covering the full IXPE operating band. For the detectors, the quantum efficiency and the modulation factor must be accurately calibrated at a series of energies covering the IXPE band. Further, as IXPE is designed to be sensitive to small degrees (few %) of polarization it is vital to test with unpolarized X rays to verify that there are no systematic effects that could give rise to spurious modulations and hence false polarizations. In fact, during detector calibration, by far the largest amount of time was spent analyzing the DU's response to unpolarized X rays. Finally, the spatial resolution of the detectors and the angular resolution of the optics must be measured at a range of energies and off-axis positions.

The requirements for IXPE calibration are based on a flow-down from the top-level science requirement to measure polarization down to a certain level for a representative sample of various classes of cosmic X-ray sources. This top-level polarization-sensitivity requirement is stated as:

*IXPE shall provide a minimum detectable polarization ( $MDP_{99}$ ) not to exceed 5.5% for a point source with an  $E^{-2}$  photon spectrum and a 2–8 keV flux of  $10^{-11}$  ergs  $cm^{-2}$  sec $^{-1}$  and an integration time of 10 days.*

This describes the level of polarization that can be measured at the 99% confidence level for a generic cosmic source spectrum, flux and integration time. A second top-level requirement concerns the angular resolution of the observatory, to perform its imaging role:

*IXPE shall have a system-level angular resolution not to exceed 30 arcsec half-power diameter (HPD).*

These two requirements in turn flow down to individual requirements on telescope effective area, telescope modulation factor, telescope spurious modulation and telescope angular resolution, all at multiple energies across the IXPE band. Derived from these, in turn, are the calibration requirements that describe the precision to which these values must be measured. These telescope on-ground calibration requirements are as follows:

1. The effective area of each MMA-DU combination shall be measured to an accuracy equal to or better than 10% of its value, on axis and at least 16 off-axis positions, for at least 3 energies between 1.5 and 8 keV.
2. The modulation factor ( $\mu$ ) of each MMA-DU combination shall be measured to an accuracy equal to or better than 1% of its value for at least 2 energies in the range 1.5 – 8.0 keV and with at least 2 dither patterns at each energy.

3. The spurious-modulation amplitude of each MMA-DU combination shall be measured to an accuracy equal to or better than 0.1% absolute value, for at least 2 energies in the range 1.5 – 8 keV and with at least 1 dither pattern at each energy.
4. The half-power diameter (HPD) of each MMA-DU combination shall be measured to an accuracy equal to or better than 3% of its value, on axis and at least 16 off-axis positions, for at least 3 energies between 1.5 and 8 keV.

The mention of dither pattern in the above requirements refers to a controlled small-amplitude (few arcmin) variation of observatory pointing planned to distribute the focused image over a small (few mm) region of the focal plane - this removes the requirement for accurately calibrating the response of every pixel in the detector. The dither pattern is designed to uniformly illuminate the detector over the dithered region.

Extensive calibrations were carried out on the MMAs at MSFC and the DUs at INAF-IAPS, Italy. The response of a telescope system could then, in theory, be synthesized by simply combining the responses of the individual optics and detectors. However, there were concerns that there were small differences in the functioning of a telescope system compared with how the individual components were tested. The most significant of these was that the detector units were all calibrated with near-parallel beams of X rays oriented normally to the detector surface. However, when placed at the focus of an X-ray optic, the X rays are now impinging in a cone, focused to the center of the detector depth, at angles that are  $4 \times$  the on-axis graze angles of the optics. For the outer shells, which provide the bulk of the effective area, these impingement angles are about 2 degrees. This affects both the spatial resolution, which is now somewhat blurred due to parallax effects, and potentially the modulation factor due to a tipping of the photoelectron emission plane. Also, the reflection of X rays can generate polarization and though this effect is calculated to be small for typical graze angles (< 0.01% polarization for a 0.5-degree graze angle following the formalism in [Almeida & Pillet \(1992\)](#)), and reduced by azimuthal symmetry, it is important to demonstrate that it does not contribute at any IXPE energy or possible off-axis angle. Finally, during DU testing it was found that spurious modulation did occur with unpolarized X rays, the cause of which was never fully understood although it was found to originate in the GEM. While this spurious modulation was stable and could therefore be calibrated out (it varied with energy and position on the detector), it was important to show that it remained the same when the detector was at the focus of an MMA, and hence that the extensive individual detector calibrations with unpolarized X rays were still valid.

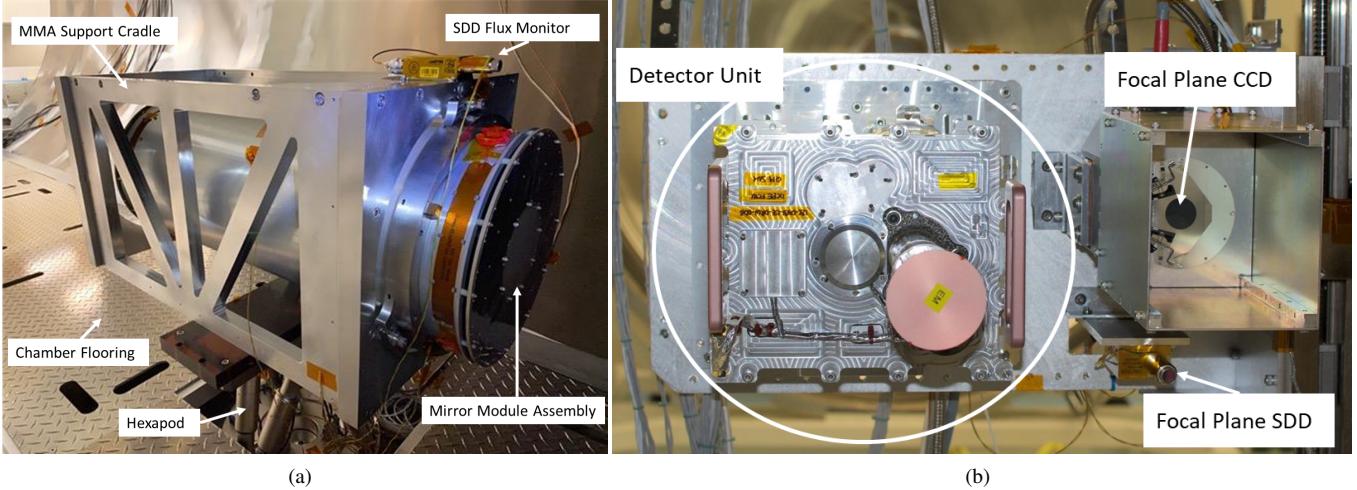
The original intention was to perform a full end-to-end calibration of each telescope system, hence the above individual telescope calibration requirements. However, as the program progressed, and various hurdles were overcome (including Covid-19 and a US Government shutdown), it became obvious that there was not enough time and funding to accomplish this, given a fixed launch date. It was therefore decided that the flight spare telescope would be fully calibrated to prove that we could accurately perform a telescope calibration by the appropriate analytical combination of the individual flight spare mirror module assembly (MMA-4) and the flight-spare detector (DU-FM1) calibrations. This would pave the way for analytical combinations for all flight telescopes by demonstrating that any effects induced by the presence of the optics were negligible within the required calibration accuracy. In this manner, the required response functions for all three flight telescopes could be confidently generated.<sup>1</sup>

#### 4. MSFC CALIBRATION FACILITY MODIFICATIONS.

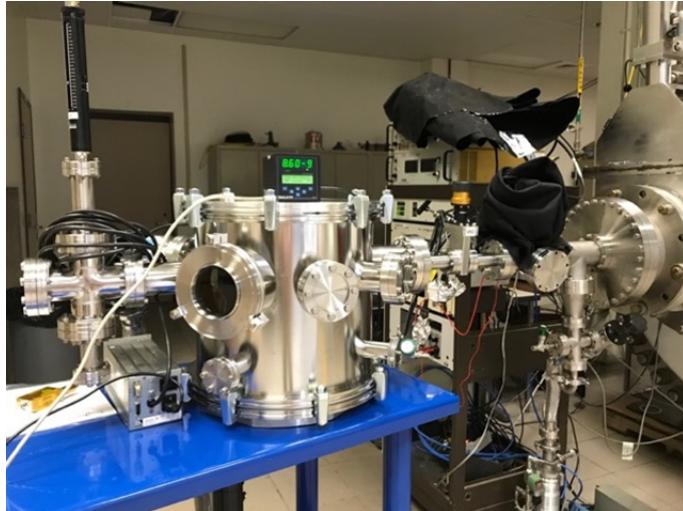
All telescope (and MMA) calibrations were carried out at the MSFC stray light test facility (now renamed the MSFC 100-m facility). As the name implies, the facility has a  $\sim$  100-m-long vacuum beam-line consisting of a 1.2-m-diameter beam tube feeding into 2.4-m-diameter by 14-m-long test chamber ([Thomas et al. 2023](#)). The test IXPE-spare MMA (MMA-4) was mounted in a cradle atop a hexapod which permitted fine control in all axes (see Figure 4(a)). The IXPE spare flight detector and facility detectors, were mounted on an XY stage system at an appropriate distance for the 100-m source distance which gave an effective focal length of 4.17 m. (Figure 4(b)).

The facility contains the typical selection of electron-impact X-ray sources with tungsten, molybdenum, iron, titanium and aluminum anodes giving characteristic lines and continuum radiation. It also has an X-ray filter system to reduce continuum emission and emphasize line emission when needed. For the IXPE telescope tests, it was also necessary to provide highly-polarized X rays covering the IXPE energy band. This was done by using crystals matched to specific X-ray lines satisfying the Bragg condition at  $\sim$  45 degrees incidence and thus giving  $>$  99% polarization. Table 3 shows the configurations used. To give adequate flux it was necessary to procure custom X-ray sources; windowless devices, water cooled with 1-mm X-ray spot sizes and capable of operating at up to 900 Watts power. As they need to be operated at high vacuum ( $< 10^{-5}$  torr), and to block visible light emitted by the sources, an optical blocking filter was installed. This permitted the source side to be kept at a lower pressure

<sup>1</sup> [https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/IXPE-SOC-DOC-011A\\_UG-Observatory.pdf](https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/IXPE-SOC-DOC-011A_UG-Observatory.pdf)



**Figure 4.** (a) IXPE MMA in test facility. (b) Focal plane test detectors including a CCD camera, a fast silicon drift detector (SDD) and the flight-spare IXPE detector unit (circled).



**Figure 5.** The test facility crystal box.

than the overall facility. The whole source assembly, with its own pumping system was mounted inside a crystal 'box' which allowed for translation and rotation of the different crystal assemblies (Figure 5)

**Table 3.** Polarized source configurations.

X-ray Tube (Line)	Crystal	Energy	Polarization
Rhodium (L)	Germanium (111)	2.7 keV	> 99% at ~45°
Titanium (K)	Silicon (220)	4.5 keV	> 99% at ~45°
Iron (K)	Silicon (400)	6.4 keV	> 99% at ~45°

The IXPE program purchased two identical Amptek Fast Silicon Drift Detectors (SDD) for use during the IXPE MMA calibrations, one detector serving as a beam monitor to measure the flux incident on the X-ray optic under test, and the other mounted for use as a focal plane detector to provide effective area measurements. The SDDs have a circular aperture of area  $50 \text{ mm}^2$ , and a Be window of nominal thickness 0.0005 inch ( $12.7 \mu\text{m}$ ). These detectors were operated with shaping-times of 1 microsecond or faster to accommodate high count rates with dead-times less than 1%, at the expense of some slight degradation in spectral resolution (but still easily meeting IXPE requirements). For characterizing the MMA Point Spread Function an Andor DW436

camera was used, having a 2048×2048 Charge Coupled Device (CCD) sensor with 13.5- $\mu\text{m}$  pixels. The DW436 is water cooled and designed to work entirely in vacuum. This camera is a back-illuminated, soft-X-ray-sensitive design with no coatings. The CCD camera has an optical blocking filter (aluminized polyimide) at its entrance and uses a Uniblitz X-ray shutter system to control integration times.

## 5. RESULTS

### 5.1. Effective Area

#### 5.1.1. Calibration Requirement

The effective area of the MMA-DU combination shall be measured to an accuracy equal to or better than 10% of its value on axis and at least 16 off-axis positions, for at least 3 energies between 1.5 and 8 keV.

#### 5.1.2. Measurements

Prior to making measurements, the DU was centered on the MMA beam and a best-focus position was obtained by minimizing the measured MMA half-power diameter. Angular resolution (half-power diameter) and effective area data were collected at the same time as MMA-4 was stepped through the required on axis and off-axis angles. As rotating the optic about its node does not move the focal image the detector must also be stepped to appropriate off-axis positions to simulate in-flight telescope performance. Table 4 shows the angles covered, and their respective nominal detector positions. These angles align with a subset of those used in MMA calibrations, allowing direct comparisons. It is worth noting that, on orbit, off-axis pointing will change the incidence angles on the detector, but as the total field of view of the telescope is quite small (7arcmin radius) compared to the 2 degree cone angle, this effect is negligible.

**Table 4.** Off-axis angles and detector positions for telescope effective area measurements.

(MMA)		Detector Offset	
(arcmin)		(mm)	
Pan (X)	Tip (Y)	X	Y
0	0	0	0
0	5.0	0	6.05
0	-5.0	0	-6.05
5.0	0	6.05	0
-5.0	0	-6.05	0
4.95	4.95	5.99	5.99
4.95	-4.95	5.99	-5.99
-4.95	4.95	-5.99	5.99
-4.95	-4.95	-5.99	-5.99
0	3.0	0	3.63
0	-3.0	0	-3.63
3.0	0	3.63	0
-3.0	0	-3.63	0
2.83	2.83	3.42	3.42
2.83	-2.83	3.42	-3.42
-2.83	2.83	-3.42	3.42
-2.83	-2.83	-3.42	-3.42

Data were taken with Mo L, Ti K, and Fe K characteristic X rays. To suppress continuum emission each source was filtered using Nb (5  $\mu\text{m}$ ), Ti (77  $\mu\text{m}$ ) and Fe (77  $\mu\text{m}$ ) respectively. A monitor counter, positioned at the MMA, was used to derive the incident flux. This SDD has precisely-known collecting area and quantum efficiency. For each energy and angle, a minimum of 1000 counts were collected in the monitor counter to give the desired effective-area accuracy. As the energy resolution of the DU is about 17% FWHM at 6.4 keV, it cannot resolve the  $K_{\alpha}$  from the  $K_{\beta}$  lines for either Ti or Fe, or the different L lines from molybdenum; therefore, a weighted mean energy was used for these measurements. The data from the monitor SDD, which has high spectral resolution, is the sum all the K lines for each source. The L lines from molybdenum are not resolved by the SDD.

The effective weighted energies for the three X-ray sources, correcting for SDD efficiency, are: 2.30 keV for Mo L, 4.63 keV for Ti K and 6.58 keV for Fe K.

### 5.1.3. Results

The data were processed using a standard moments analysis (Baldini et al. 2021). Because the gas detector has limited energy resolution and has tailing - lower energy events present due to incomplete charge collection - the acceptance band of the DU was opened to  $+ 3\sigma$  above the peak pulse height and also included everything below the peak. Similarly, as discussed above, the acceptance band of the SDD detector was opened to include all  $K_{\alpha}$  and  $K_{\beta}$  lines plus any escape peaks (from silicon fluorescence escaping the detector) or tailing (from incomplete charge collection) present in the data. The DU data were corrected for deadtime and the resulting count rate was divided by the rate in the SDD flux monitor (the same one that was used for MMA calibration), and multiplied by the flux-monitor area. Finally, the resulting effective areas were scaled to that for infinite source distance, using energy and off-axis-angle dependent correction factors derived from ray-trace models.

The resulting data are shown below for each energy in Tables 5, 6, 7, 8. The uncertainties for each measurement (statistical plus uncertainties in detector response and geometry) are given in table captions 6,7,8.

The on-axis effective area for the MMA alone was measured during MMA calibration using a pair of identical, fast SDDs, one (near the MMA entrance aperture) monitoring the input flux and the other at the mirror focus. The ratio of the two count rates, adjusted for minor response differences measured during cross calibration, multiplied by the monitor's active area gave the effective area of the optic as a function of energy.

**Table 5.** Comparison of predicted and measured telescope on-axis effective areas. Difference column is (measured-predicted)/average value, expressed as a percentage.

Source	Mean Energy $K_{\alpha}+K_{\beta}$ (keV)	Measured MMA Effective Area (cm <sup>2</sup> )	DU quantum efficiency	Predicted Telescope Effective Area (cm <sup>2</sup> )	Measured Effective Area (cm <sup>2</sup> )	Difference %
Mo	2.30	163.2	0.155	25.23	25.34	0.4
Ti	4.63	195.7	0.0382	7.48	7.39	-1.3
Fe	6.58	176.1	0.0152	2.68	2.82	4.9

To derive a predicted telescope on-axis effective area from separate MMA and DU calibrations, the MMA effective area (corrected to infinite source distance) was combined with the DU quantum efficiency (QE) appropriate for the telescope calibration at MSFC. This required adjusting the efficiency measured during the DU calibration at IAPS, to correct for a small (few mbar) pressure drop (thought to be due to absorption of the DME by epoxy used in the GPD construction) between that date and the calibration date at MSFC, using empirical models developed in Italy (Baldini et al. 2021). It is also very important that the appropriate weighted mean source energy is used when deriving the appropriate DU quantum efficiency as the QE changes with energy.

The results of this comparison between the predicted on-axis telescope effective area and the measured effective area, are shown in Table 5 at 3 energies with both data sets corrected to infinite source distance. Statistical and systematic errors are approximately 3% for the predicted effective area ( $1-\sigma$ ) and 5%, 4% and 2% respectively ( $1-\sigma$ ) for the measured effective areas at 2.3 keV, 4.6 keV and 6.6 keV respectively. It can be seen that the predicted and measured telescope effective areas are within statistical errors (at  $1.3-\sigma$  for the 6.6 keV case) for these on-axis measurements, as expected. The same process was repeated at each energy for all off-axis angles in Table 4. For these, MMA effective areas were measured at a subset of angles using the SDDs (17 angles at 2.3 keV and 5 angles at 4.6 keV and 6.6 keV), then interpolated using CCD data taken at every angle. The resulting effective area data are shown in Tables 6–8.

### 5.1.4. Discussion

It is clear that there is reasonable agreement between the predicted and measured off-axis effective areas for all energies tested. The captions for Tables 6,7,8 give the mean difference and standard deviation for all the off-axis measurements at each specific energy. These mean values show there is a small energy-dependent offset that is around -5% at 2.3 keV, -3 % at 4.6 keV and 1.5% at 6.6 keV. The standard deviation around these means is consistent with the estimated uncertainties in the measurements. These small offsets, decreasing in absolute amplitude with energy, are well within the required calibration accuracy, and are thought to be due to a possible error in the energy-dependent quantum efficiency of the detector calculated for the time of calibration.

**Table 6.** Comparison of measured and predicted effective areas (EA) at 2.3 keV. Effective area  $1-\sigma$  uncertainties are  $\sim \pm 3\%$  for predicted values and  $\pm 5\%$  for measured values. Difference column is (measured-predicted)/average value, expressed as a percentage. The mean difference value over the data set is -5.0%, with a standard deviation of 4.1%.

MMA (arcmin)	Predicted Telescope	Measured Telescope	Difference %
Pan (X)	Tip (Y)	EA (cm <sup>2</sup> )	EA (cm <sup>2</sup> )
0	0	25.2	25.3
0	5.0	19.3	18.9
0	-5.0	19.3	17.7
5.0	0	19.2	18.1
-5.0	0	19.2	19.0
4.95	4.95	16.7	17.0
4.95	-4.95	16.6	14.6
-4.95	4.95	16.6	15.7
-4.95	-4.95	16.7	15.4
0	3.0	22.2	21.4
0	-3.0	22.2	20.9
3	0	22.1	19.9
-3	0	22.1	22.4
2.83	2.83	20.7	20.0
2.83	-2.83	20.6	19.1
-2.83	2.83	20.6	19.2
-2.83	-2.83	20.7	19.7

**Table 7.** Comparison of measured and predicted effective areas (EA) at  $\sim 4.6$  keV. Effective area  $1-\sigma$  uncertainties are  $\sim \pm 3\%$  for predicted values and  $\pm 4\%$  for measured values. Difference column is (measured-predicted)/average value, expressed as a percentage. The mean difference value over the data set is -3.0%, with a standard deviation of 3.1%.

MMA (arcmin)	Predicted Telescope	Measured Telescope	Difference %
Pan (X)	Tip (Y)	EA (cm <sup>2</sup> )	EA (cm <sup>2</sup> )
0	0	7.5	7.4
0	5.0	5.8	5.6
0	-5.0	5.8	5.5
5.0	0	5.7	5.6
-5.0	0	5.7	5.6
4.95	4.95	4.9	4.7
4.95	-4.95	4.9	4.7
-4.95	4.95	4.9	4.5
-4.95	-4.95	5.0	4.5
0	3.0	6.6	6.5
0	-3.0	6.6	6.2
3.0	0	6.5	6.7
-3.0	0	6.5	6.7
2.83	2.83	6.1	5.9
2.83	-2.83	6.1	6.2
-2.83	2.83	6.1	6.0
-2.83	-2.83	6.1	5.9

**Table 8.** Comparison of measured and predicted effective areas (EA) at  $\sim 6.6$  keV. Effective area  $1-\sigma$  uncertainties are  $\sim \pm 3\%$  for predicted values and  $\pm 2\%$  for measured values. Difference column is (measured-predicted)/average value, expressed as a percentage. The mean difference value over the data set is 1.5%, with a standard deviation of 2.7% .

MMA (arcmin)	Predicted Telescope	Measured Telescope	Difference %
Pan (X)	Tip (Y)	EA (cm <sup>2</sup> )	EA (cm <sup>2</sup> )
0	0	2.68	2.82
0	5.0	1.70	1.71
0	-5.0	1.70	1.74
5.0	0	1.76	1.75
-5.0	0	1.76	1.76
4.95	4.95	1.38	1.36
4.95	-4.95	1.34	1.31
-4.95	4.95	1.34	1.30
-4.95	-4.95	1.38	1.35
0	3.0	2.15	2.27
0	-3.0	2.15	2.26
3.0	0	2.18	2.28
-3.0	0	2.18	2.23
2.83	2.83	1.92	1.97
2.83	-2.83	1.91	1.97
-2.83	2.83	1.91	1.97
-2.83	-2.83	1.92	1.98

### 5.2. Modulation Factor

#### 5.2.1. Calibration Requirements

The modulation factor ( $\mu$ ) shall be measured to an accuracy equal to or better than 1% of its value for at least 2 energies in the range 1.5–8.0 keV and with at least 2 dither patterns at each energy.

#### 5.2.2. Measurements

The measurement of the telescope modulation factor started with characterization of the width of the polarized beam for each source, generated by diffracting X-rays from a nominal point source off specific crystals at precise angles. This characterization was necessary as the width of the polarized beam in the dispersion direction was significantly less than the width of the MMA, thus the beam must be stepped through multiple positions to ensure uniform coverage of the optic. The beam characterization is performed, for each polarized source, by driving the MMA to its out-of-focus position (+ 50 mm from true focus) and acquiring an image on the focal plane CCD detector. Analysis of this ring image showed the extent of coverage by the beam, and allowed calculation of the number of discrete steps (achieved typically by 0.035° rotations of the crystal) needed to give uniform MMA coverage. These images at discrete steps were summed and the resulting ring image analyzed for uniformity. When acceptable (greater than 90% uniformity across the MMA active surface), these parameters were recorded for use when making the modulation factor measurement. This process was repeated for all sources used.

Telescope modulation factors were measured for three source + crystal combinations (see Table 3), with source energies and crystal lattice spacing chosen to achieve Bragg angles close to 45°. Consequently, the resulting X-ray beams are nearly totally (linearly) polarized. For all measurements of modulation factors, dithering of the MMA was used to simulate the dithering planned for use on orbit. This dithering also approximately aligns with that used for detector calibrations at INAF-IAPS. Two dithering values were used for the telescope calibration: 1.78 mm radius and 3.57 mm radius, implemented by lateral motions of the MMA-supporting hexapod. The dithering pattern was a Lissajous-type figure, designed to provide near uniform coverage of the dither area. The required detector counts to achieve the required 1% accuracy in measured modulation factor are given in Table 9, along with the actual counts accrued during the measurement.

**Table 9.** Modulation factor measurement dither and count parameters.

Source	Dither Radius (mm)	Counts Required	Counts Accrued
Rh (L)	1.78	$3.5 \times 10^5$	$1.2 \times 10^6$
Ti (K)	1.78	$1.2 \times 10^5$	$2.9 \times 10^5$
Fe (K)	1.78	$8.6 \times 10^4$	$1.9 \times 10^5$
<hr/>			
Rh (L)	3.57	$1.1 \times 10^6$	$1.6 \times 10^6$
Ti (K)	3.57	$4.0 \times 10^5$	$7.1 \times 10^5$
Fe (K)	3.57	$2.9 \times 10^5$	$5.8 \times 10^5$

#### 5.2.3. Results

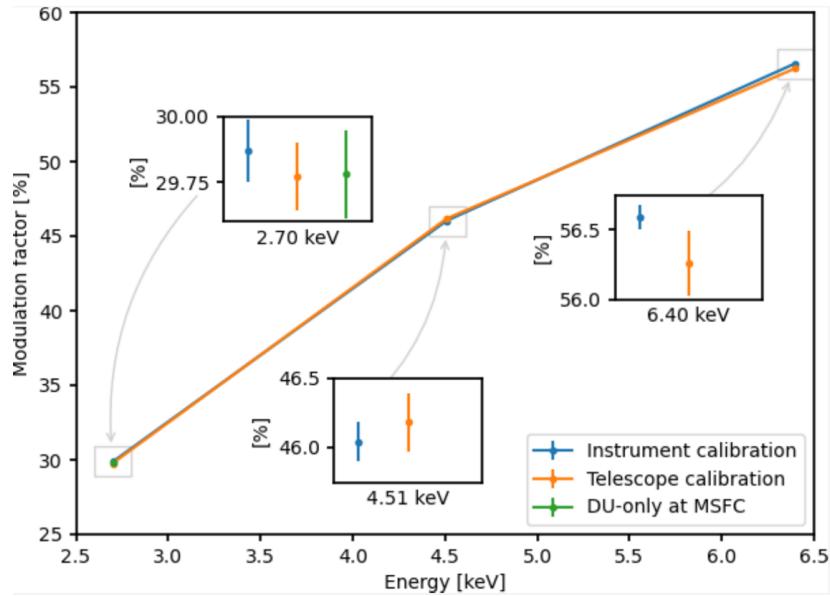
In order to accurately assess the modulation factor it was necessary to remove any spurious modulation measured for each energy during the separate calibration of this detector. Then the DU data were processed using a standard moments analysis with a 20% cut on tracks, based on track ovality, and an energy cut of  $\pm 3\sigma$  around all line energies (see Baldini et al. (2021) for a description of detector data analysis). The measured modulation factors for the telescope are then compared to those measured for the DU alone during detector calibration by IAPS at INAF-IAPS. The results are shown in Table 10, together with the  $1-\sigma$  measurement errors, and in Figure 6.

As an additional check that nothing had changed between the original detector calibration at INAF-IAPS and the telescope calibration much later at MSFC, an additional set of data was taken at the Stray Light Test Facility, moving the detector unit so that it viewed the polarized source directly, rather than through the MMA. Because the DU is rate limited to  $\sim 150$  c/s it was necessary to electronically mask the DU to accept only events within a 3-mm-radius circle to approximate the dither area with the MMA. In this way the full 150 c/s could be applied to the central region and the desired number of counts could be obtained in a reasonable timescale. These results are shown in Table 11.

#### 5.2.4. Discussion

**Table 10.** Measured telescope and DU modulation factors. Difference column is detector value-telescope value.

Source (Energy)	Dither Radius (mm)	Telescope Modulation Factor		Detector Modulation Factor DU-FM1 @ IAPS	Difference
		DU-FM1	%		
Rh L (2.7 keV)	1.78	$29.69 \pm 0.20$		$29.87 \pm 0.12$	0.18
Ti K (4.5 keV)	1.78	$45.43 \pm 0.33$		$46.04 \pm 0.14$	0.61
Fe K (6.4 keV)	1.78	$57.08 \pm 0.42$		$56.59 \pm 0.09$	-0.49
<hr/>					
Rh L (2.7 keV)	3.57	$29.77 \pm 0.13$		$29.87 \pm 0.13$	0.10
Ti K (4.5 keV)	3.57	$46.18 \pm 0.21$		$46.04 \pm 0.14$	-0.14
Fe K (6.4 keV)	3.57	$56.26 \pm 0.23$		$56.59 \pm 0.09$	0.33

**Figure 6.** The summary of the modulation factor calibration at MSFC and at INAF-IAPS (3.57 mm dither) showing good agreement.**Table 11.** Measurements of modulation factors for DU-FM1 at MSFC, with and without optics, compared with those taken at INAF-IAPS.

Source / Energy	Modulation Factor	Modulation Factor	Modulation Factor
	DU-FM1 at MSFC	DU-FM1 + MMA4	DU-FM1 @ IAPS
Rh L (2.7 keV)	$29.78 \pm 0.17$ %	$29.77 \pm 0.13$ %	$29.87 \pm 0.12$ %

The above data show that the requirement for the number of energies and for statistical precision of modulation factor measurements were met. Table 10 and Table 11 show that modulation factors measured with the telescope are equal to those measured with the DU alone within the statistical uncertainties. This shows that for the modulation factor the telescope response can be derived from the DU calibration data alone, and that there are no discernible MMA-induced effects.

### 5.3. Spurious Modulation

#### 5.3.1. Calibration requirement

The spurious-modulation amplitude shall be measured to an accuracy equal to or better than 0.1% absolute value, for at least 2 energies in the range 1.5–8 keV and with at least 1 dither pattern at each energy.

### 5.3.2. Measurements

This measurement utilizes low-flux non-polarized X-ray sources to evaluate low-level modulation inherent in the response of the detector. The collected counts required to do this at the required absolute accuracy (0.1%) are given in Table 12, along with the total counts accrued during the measurement.

The X-ray sources, however, can have a small degree of residual polarization, due to the way the X rays are generated. In electron-impact X-ray sources, those sources with end windows, where the emitted X-rays are parallel to the electron direction, exhibit no polarization whereas those sources whose X-ray emission is perpendicular to the electron beam show intrinsic polarization (Ratheesh et al. 2023). As the sources used in the IXPE telescope calibration are of the latter kind, this source polarization must be removed from the data. This is accomplished, for each X-ray source, by splitting the measurement in two and rotating the x-ray head by 90 degrees for the second half of the accumulation. Adding together the two halves then cancels out the effects of any intrinsic polarization of the source.

As with the modulation factor measurements, the optic was dithered with a radius of 3.57 mm. However, for the aluminum source the hexapod dither had become unreliable (a lubrication issue) and so the image was spread by simply defocusing the optic by 50 mm to give a suitably sized focal region.

**Table 12.** Spurious modulation measurements dither and count parameters.

Source / Energy	Dither Radius (mm)	Counts Required	Counts Accrued
Mo L (2.3 keV)	3.57	$3.0 \times 10^6$	$3.3 \times 10^6$
Ti K (4.6 keV)	3.57	$3.0 \times 10^6$	$3.2 \times 10^6$
Fe K (6.6 keV)	3.57	$3.0 \times 10^6$	<sup>a</sup> $2.6 \times 10^6$
Al K (1.5 keV)	Not dithered, but defocused	$3.0 \times 10^6$	$3.1 \times 10^6$

<sup>a</sup> Note that the required counts for Fe were not precisely achieved due to problems with the dither near the end of the run. Nevertheless, the calibration requirement of ‘at least 2 energies’ was met.

### 5.3.3. Results

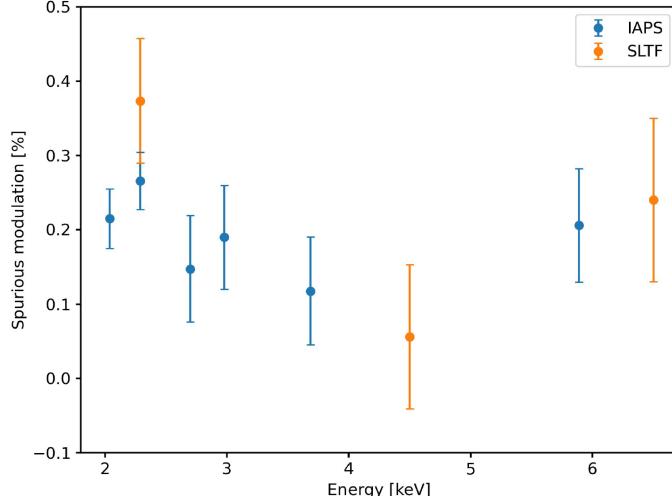
Data were processed without applying any track cuts. Table 13 shows the spurious modulation results for the four sources with the intrinsic source modulation removed as described above. For the aluminum source the data were taken from a defocused ring image (no dithering) and analyzed within a 1.5-mm radius. Measured amplitudes of the intrinsic source modulations, which reflect an intrinsic polarization of the X-ray sources, is given in Table 14 for reference.

**Table 13.** Telescope spurious modulation measurements after X-ray source modulation removal.

Source / Energy	Mod (%)	Mod-error (%)
Mo L (2.3 keV)	0.373	0.084
Ti K (4.6 keV)	0.056	0.097
Fe K (6.6 keV)	0.24	0.11
Al K (1.5 keV)	0.5	0.11

**Table 14.** Measured modulations from the calibration electron-impact sources.

Source / Energy	Mod (%)	Mod-error (%)
Mo L (2.3 keV)	0.254	0.085
Ti K (4.5 keV)	0.503	0.097
Fe K (6.4 keV)	0.28	0.11
Al K (1.5 keV)	0.441	0.089



**Figure 7.** Spurious modulation measurements at MSFC compared with data taken at INAF-IAPS on a flat field illumination of 3.57 mm radius

**Table 15.** Spurious modulation measurement results at 2.3 keV with and without MMA-4 and and an extraction region of 3.3 mm radius at MSFC.

Source /Energy	Mod (%)	Mod-error (%)	MMA present
Mo L (2.3 keV)	0.531	0.089	Yes
Mo L (2.3 keV)	0.41	0.10	No

Figure 7 compares the spurious modulation measured at 3 energies during telescope calibration at MSFC (orange) with measurements of the detector (DU-FM1) at IAPS (blue). Although the energies are not all the same, it is evident that the two data sets are in good agreement ( $1-\sigma$  errors shown).

An additional set of measurements were performed at SLTF at 2.3 keV, where the spurious modulation was measured for the telescope and then for DU-FM1 alone, after moving from behind the optic so that it was directly illuminated by the source. For the latter measurement, an electronic mask was applied to the DU so that only events within the dither radius were registered (as for the modulation factor measurements). Note that this extraction radius was 10% smaller than for the data in Figure 7, and as the spurious modulation is position dependent the small difference between the data at 2.3 keV in Figure 7 and Table 15 is to be expected.

#### 5.3.4. Discussion

The above data show first that the requirement for spurious modulation measurement was met for the telescope calibration: At least two energies were used, and a statistical precision of  $\leq 0.1\%$  absolute (see Mod-error column of Table 13 ) was achieved for two energies, and within rounding errors, for an additional 2 energies.

The data also show that the MMA has no effect on spurious modulation. Figure 7 compares data taken during telescope calibration with data taken with the same DU-FM1 during detector calibration at INAF-IAPS. These spurious modulation data are in good agreement. Table 15 shows measurements at 2.3 keV both at the focus of MMA4 and then in the direct beam at the SLTF without the optic. The spurious modulation (Mod %) for the two measurements are within  $1-\sigma$  of each other (see Mod-error column) and so are statistically identical. As with the modulation factor, the spurious modulation is unchanged by the presence of the optic.

### 5.4. Half Power Diameter

#### 5.4.1. Calibration Requirement

The half-power diameter (HPD) of each MMA-DU combination tested shall be measured to an accuracy equal to or better than 3% of its value, on axis and at least 16 off-axis positions, for at least 3 energies between 1.5 and 8 keV.

#### 5.4.2. Measurements

As for the effective area measurements, DU-FM1 was decentered and a best focus position was obtained, minimizing the measured angular resolution. The required HPD data and effective area data were collected simultaneously stepping through the optic angles and appropriate detector positions that were given in Table 4.

The half-power diameter of each MMA was measured using the Andor CCD camera at the focus of the optic, with filtered X-ray sources producing lines at nominally 2.3 keV (MoL), 4.6 keV (TiK) and 6.6 keV (FeK) along with some continuum emission. The detector region used for this measurement was chosen to be the same as that used for the effective area, i.e. a circle of diameter 8 mm, which is approximately 16 times the MMA HPD. Flat fields, taken immediately before and after the measurements, were used to subtract offsets and noise contributions in individual pixels. The diameter containing half the flux within the measurement region was then determined and converted to an angle using the measured image distance ( $\sim 4.17\text{m}$ ) for the 100-m object distance at the SLTF.

For the telescope, the HPD was measured at the same energies as was the MMA, using the same 8-mm-diameter circular region on the DU. As with the MMA, the diameter containing half the flux within this region was calculated and converted to an angle, again using the same measured focal distance (image distance).

It is expected that the telescope and MMA HPDs will differ slightly. This is because the DU adds additional blurring to the image due to its finite spatial resolution (limited by the ability to determine the beginning of a track) and by the finite depth of the detector (10 mm), which adds additional defocusing of the image due to gas transparency and the cone angle of X rays focused by the mirror assembly. However, these two components are small compared to the native MMA resolution.

The detector spatial resolution was measured during calibration at INAF-IAPS. An additional factor has been added to these reported spatial resolutions to account for an  $0.8^\circ$  misalignment (estimated after the calibration) of the DU with respect to the X-ray axis during the telescope calibration.

Defocusing effects, due to finite detector gas depth, were calculated via Monte-Carlo simulations. An initial value for this contribution, modeled for a perfect optic, to be added in quadrature to the native optic resolution was found to be 8.1 arcsec. However, using measured MMA figure and circularity errors in the simulation increased this effect to 9.4 arcsec, independent of energy as the X-ray mean-free-path is larger than the detector depth at all tested energies. As a check on this Monte-Carlo approach, results were also obtained by taking a series of CCD images over a  $\pm 5\text{ mm}$  region centered on the optimum focal distance, to span the region covered by the thickness of the detector gas cell. Summing these CCD images effectively blurs the image in a way similar to that due to the gas depth in the DU. These measurements agreed well with the Monte-Carlo simulations (within one arcsecond).

#### 5.4.3. Results

Table 16 shows the results of the on-axis HPD comparison. MMA HPD represents the angular resolution of the MMA measured with the CCD camera. Detector spatial resolution and defocusing effects, converted to HPD in arcsec, are summed in quadrature with the native MMA resolution to give the predicted telescope angular resolution. The next column shows the measured telescope HPD obtained during telescope calibration. Estimated uncertainties are  $\sim 2\%$  ( $1-\sigma$ ) for the predicted HPD measurements and  $\sim 0.5\text{-}1\%$  for the measured value. As can be seen from the table, the predicted and measured telescope HPDs are in reasonable agreement given measurement uncertainties.

**Table 16.** Comparison of predicted and measured on-axis telescope angular resolution.

X-ray Tube (Line)	MMA HPD (arcsec)	Detector Spatial Resolution (arcsec)	Detector Defocusing Effects (arcsec)	Predicted Telescope HPD (arcsec)	Measured Telescope HPD (arcsec)	Difference %
2.3 keV	20.0	5.6	9.4	22.8	22.2	-2.7
4.6 keV	20.8	6.3	9.4	23.7	23.8	0.6
6.6 keV	20.1	7.4	9.4	23.4	24.1	2.8

This same process was repeated, at each energy, for all off-axis angles (Tables 17–19).

The maps of the source images for different off-axis angle are shown in Figures 8(a), 9(a) and 10(a) for 2.3 keV, 4.5 keV and 6.4 keV, respectively, while the corresponding models of the PSFs, based on Equation 2, are shown in Figures 8(b), 9(b) and 10(b).

$$PSF(r) = We^{-\frac{r^2}{2\sigma^2}} + N \times (1 + (\frac{r}{r_c})^2)^{-eta} + M \times (r + Offset)^{index} \quad (2)$$

**Table 17.** Comparison of predicted and measured telescope angular resolution at 2.3 keV HPD 1- $\sigma$  uncertainties are  $\sim \pm 2\%$  for predicted values and  $\pm 0.5\%$  for measured values. Difference column is (measured-predicted)/average value, expressed as a percentage. The mean difference value over the data set is -2.1%, with a standard deviation of 2.6%.

MMA (arcmin)	Predicted Telescope HPD (arcsec)	Measured Telescope HPD (arcsec)	Difference %
Pan (X)	Tip (Y)		
0	0	22.8	-2.7
0	5.0	24.2	-3.0
0	-5.0	24.1	-1.5
5.0	0	24.1	3.1
-5.0	0	24.2	-3.6
4.95	4.95	24.9	-1.0
4.95	-4.95	25.7	1.5
-4.95	4.95	25.9	-8.3
-4.95	-4.95	25.7	-5.8
0	3.0	23.5	-1.9
0	-3.0	23.5	-1.9
3.0	0	23.9	-0.8
-3.0	0	23.6	-2.9
2.83	2.83	23.9	0.3
2.83	-2.83	24.2	-0.9
-2.83	2.83	23.9	-3.5
-2.83	-2.83	24.1	-2.7

**Table 18.** Comparison of predicted and measured telescope angular resolution at 4.6 keV HPD 1- $\sigma$  uncertainties are  $\sim \pm 2\%$  for predicted values and  $\pm 1\%$  for measured values. Difference column is (measured-predicted)/average value, expressed as a percentage. The mean difference value over the data set is 1.4%, with a standard deviation of 2.3%.

MMA (arcmin)	Predicted Telescope HPD (arcsec)	Measured Telescope HPD (arcsec)	Difference %
Pan (X)	Tip (Y)		
0	0	23.7	0.6
0	5.0	25.4	0.7
0	-5.0	25.6	-0.5
5.0	0	25.1	4.3
-5.0	0	25.5	-0.1
4.95	4.95	26.2	0.7
4.95	-4.95	27.1	2.9
-4.95	4.95	26.8	-3.6
-4.95	-4.95	26.8	-1.5
0	3.0	24.4	2.5
0	-3.0	24.4	2.6
3.0	0	24.5	5.0
-3.0	0	24.8	0.6
2.83	2.83	24.9	3.4
2.83	-2.83	24.9	4.3
-2.83	2.83	24.8	-0.2
-2.83	-2.83	25.1	1.3

**Table 19.** Comparison of predicted and measured telescope angular resolution at 6.6 keV HPD 1- $\sigma$  uncertainties are  $\sim \pm 2\%$  for predicted values and  $\pm 1\%$  for measured values. Difference column is (measured-predicted)/average value, expressed as a percentage. The mean difference value over the data set is 5.7%, with a standard deviation of 2.6%.

MMA (arcmin)	Predicted Telescope HPD (arcsec)	Measured Telescope HPD (arcsec)	Difference %
Pan (X)	Tip (Y)		
0	0	23.4	2.8
0	5.0	25.2	4.1
0	-5.0	25.9	7.7
5.0	0	25.2	7.8
-5.0	0	25.9	3.0
4.95	4.95	25.9	3.9
4.95	-4.95	26.7	7.7
-4.95	4.95	26.8	1.2
-4.95	-4.95	26.6	3.0
0	3.0	24.4	7.2
0	-3.0	24.6	7.9
3.0	0	24.5	8.7
-3.0	0	24.9	4.8
2.83	2.83	24.5	9.4
2.83	-2.83	25.2	9.1
-2.83	2.83	25.0	5.1
-2.83	-2.83	25.1	4.2

The Encircled Energy Function (EEF) is defined as:

$$EEF(r) = \int_0^r PS F(r) 2\pi r dr \quad (3)$$

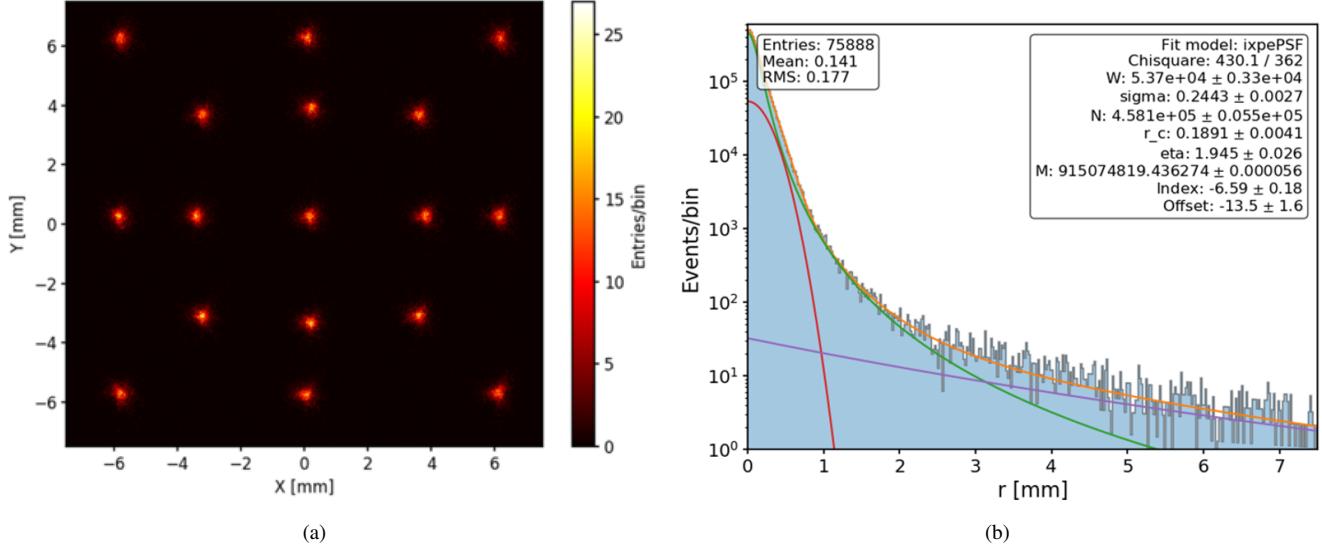
and the HPD is defined as  $HPD = 2 \times R$  where  $EEF(R) = 0.5 \times EEF(r_{max})$  with  $r_{max} = 8$  mm.

#### 5.4.4. Discussion

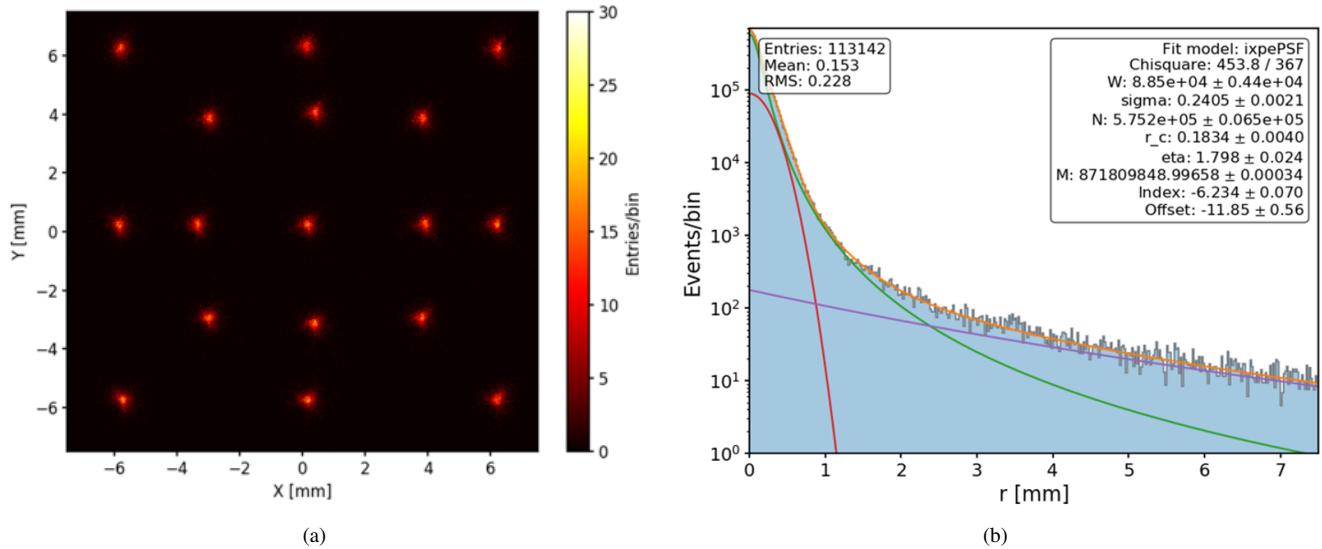
The tables 17–19 show that the predicted and measured telescope angular resolutions are in reasonable agreement. At each energy, taking the dataset as a whole, there is a small offset (measured minus predicted) in resolution plus a statistical fluctuation around that offset. For all energies, the statistical fluctuations are around 2–3% (1- $\sigma$ ), consistent with the estimated measurement uncertainties (see Table captions). The offset in HPD values is -2.1% for 2.3 keV, 1.4% for 4.6 keV, and 5.7% for 6.6 keV. The fact that there is a very slight underestimate at lower energies and a slight overestimate (amounting to about 1.5 arcsec) at higher energies remains a mystery. It should be noted that, despite these small differences, the on-axis measured telescope angular resolution in flight is still well within requirements at all energies. Since launch, the angular resolution of the flight system (3 telescopes combined) has been regularly measured using point sources and still (nearly 3 years after launch) meets its system level requirement ( $\leq 30$  arcsec HPD). Figures 8(a), 9(a) and 10(a) illustrate that the PSF is well behaved even near the edge of the field-of-view, which is essential when mapping polarization from extended sources.

## 6. CONCLUSION

The principal goal of the telescope on-ground calibration, carried out using flight-spare units, was to demonstrate that, to the accuracy required in the calibration plan, the performance of each flight telescope could be synthesized from the substantial amount of calibration data that were collected on the individual flight mirror modules and flight detector units, in the U.S and Italy, respectively. Areas of concern were that detector calibrations were performed with nominally parallel beams of X rays while near the focus of an optic, the input beam is a converging, then diverging cone of X rays. This could potentially affect the modulation factor, and the spurious modulation inherent in all the detectors, rendering their calibrations inaccurate. It can also have an effect on the spatial resolution of the detector, due to the transparency of the fill gas and the finite detector depth, which



**Figure 8.** (a) Source images obtained at an average energy of 2.3 keV demonstrates good off-axis performance compared to on-axis performance. (b) The on-axis PSF of the telescope is modeled as the sum of a Gaussian core and a King function, along with a power-law component that dominates the outer regions of the field of view.



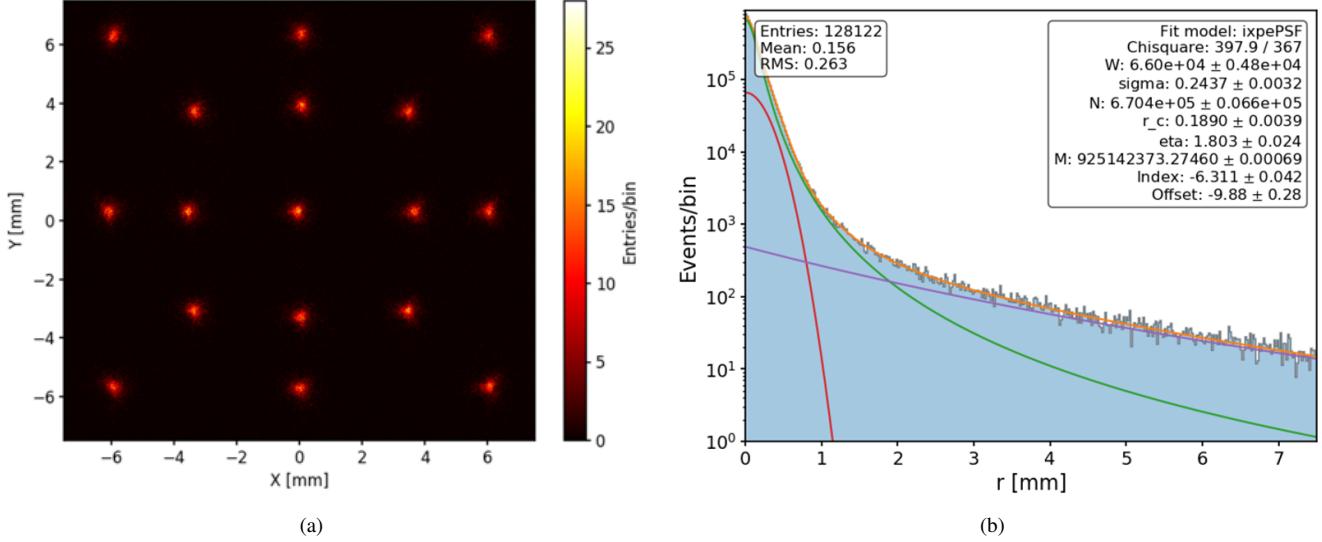
**Figure 9.** (a) Source images obtained at an average energy of 4.6 keV. (b) The on-axis PSF of the telescope is modeled as the sum of a Gaussian core and a King function, along with a power-law component that dominates the outer regions of the field of view.

must be modeled accurately to incorporate. Finally, X-ray reflection can affect the polarization measured from a source, although this effect is calculated to be very small for typical graze angles.

The data taken here show that the inclusion of the mirror module does not affect the polarization response of the detectors within the accuracy required for IXPE calibration and that the telescope angular resolution can be determined. Thus, the original stand-alone calibrations of the flight MMAs and the flight detector units can be used in full to derive the telescope calibrations.

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**Figure 10.** (a) Source images obtained at an average energy of 6.6 keV. (b) The on-axis PSF of the telescope is modeled as the sum of a Gaussian core with a King function, along with a power-law component that dominates the outer regions of the field of view.

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