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On-ground characterization of the IXPE polarization angle knowledge

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ABSTRACT

The Imaging X-ray Polarimetry Explorer (IXPE) has been recently selected for development as part of NASA's Small Explorer program (SMEX), with a launch date in 2021. Developed in a collaboration between NASA and the Italian Space Agency (ASI), IXPE will perform groundbreaking measurements of imaging polarization in X-rays for a number of different classes of sources including isolated and accreting neutron stars, pulsar wind nebulae, stellar and supermassive black holes. Combining 30 arcsec (HPD) grazing-incidence X-ray optics with the polarization-sensitive Gas Pixel Detectors (GPDs), IXPE will provide two-orders of magnitude improvement in sensitivity over the past flown instruments. The IXPE requested precision on the measurement of the polarization angle (better than 0.2 degrees at instrument level) poses strict constraints on the detector unit (DU) mechanical design and requires the implementation of a specific alignment and measurement strategy to meet the scientific requirements. In this paper we describe the design solutions that will be implemented in the DU flight models as well as a step-by-step metrology procedure that will ensure the fulfillment of the scientific requirement.

Keywords: IXPE, Imaging X-ray Polarimetry Explorer, polarization, calibration, alignment, metrology

1. INTRODUCTION

The Imaging X-ray Polarimetry Explorer[1] (IXPE) will expand understanding of high-energy astrophysical processes and sources, in support of NASA's first science objective in Astrophysics: "Discover how the universe works." The strategy for pursuing this goal is to obtain X-ray polarimetry and polarimetric imaging of cosmic sources and to use the unique information in those observations to determine the radiation processes and the detailed properties of specific cosmic X-ray sources or categories of sources as well as to explore general relativistic and quantum effects in extreme environments.

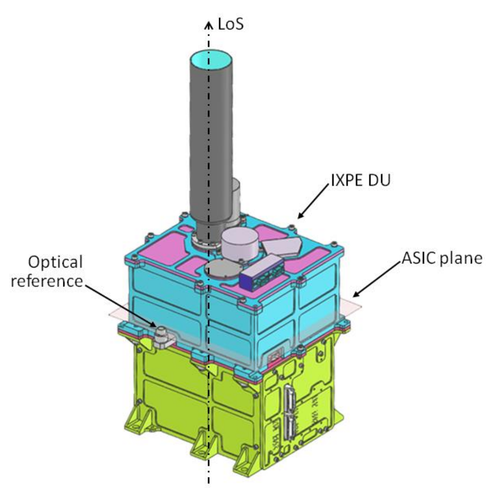

Figure 1 IXPE Detector Unit (DU) assembly with one of the three coplanar optical reference shown.

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The IXPE payload consists of a set of three identical telescope systems co-aligned with the pointing axis of the spacecraft. Each system, operating independently, comprises a 4 m focal-length Mirror Module Assembly (MMA) that focuses X-rays onto a polarization-sensitive imaging detector separated by a deployable boom. Each Detector Unit (DU) contains its own electronics, which communicate with the payload computer that in turn interfaces with the spacecraft. In addition, each DU has a multi-function filter wheel assembly that permits in-flight calibration checks, source flux attenuation and background assessments.[2]

At the very heart of each DU (Figure 1) is the polarization-sensitive imaging Gas Pixel Detector[3,4] (GPD). This detector utilizes the anisotropy of the emission direction of photoelectrons produced by polarized photons to gauge with high sensitivity the polarization state of X-rays interacting in a gaseous medium. The polarization angle (PA) of an astrophysical source is estimated by the distribution of the photoelectron emission directions as measured in the GPD ASIC reference system, defined by the orientation and position of the ASIC pixels. The Instrument contribution to the knowledge of the polarization angle can be thus translated into the knowledge of the ASIC reference system with respect to the spacecraft (S/C) Fixed Frame on the plane orthogonal to the Line of Sight (LoS). In the following sections we discuss the contribution to the knowledge of the polarization angle due to the knowledge of the GPD ASIC orientation with respect to the IXPE coordinate system.

2. IXPE GPD ASIC

The ASIC (left and center panel of Figure 2) constitutes the multiple anode of the MicroPattern Gas Pixel Detector. The chip is organized in 105600 pixels (300 × 352) with an overall active area of ~15 mm × 15 mm. The top metal layer of the 0.18 μm VLSI CMOS pixel array is patterned in hexagonal pixels with a 50 μm pitch. Each hexagonal pad is circumscribed to a 47.5 μm diameter circle with a gap between two adjacent pads of 2.5 μm. A schematic drawing of the ASIC pixel arrangement is shown in the right panel of Figure 2 (all measures are in μm).

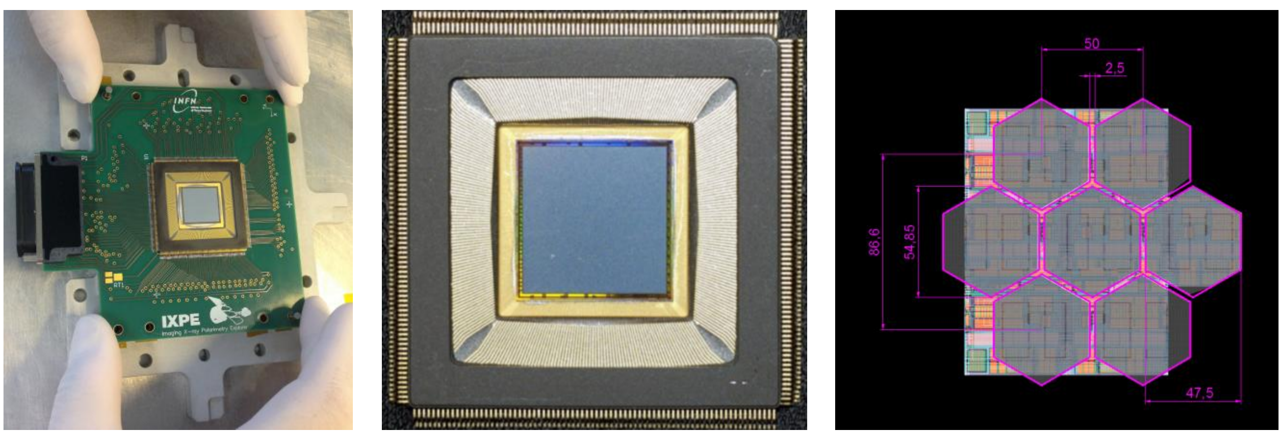


Figure 2 IXPE GPD ASIC and dimensions of the hexagonal pads constituting the anodes of the Gas Pixel Detector.

2.1 ASIC metrology measurements

After the integration of the ASIC on the front-end PCB (Figure 2, left panel), the ASIC coordinate system (CS_{ASIC}) will be determined by means of a Mitutoyo BHN 506 coordinate measuring machine (CMM) at the INFN Pisa laboratory. The CMM Maximum Permissible Error (MPE) is 3.0 + (4L / 1000) μm, where L is the measured length in meters. In the following analysis we conservatively consider this value as the 1-σ CMM positioning error.

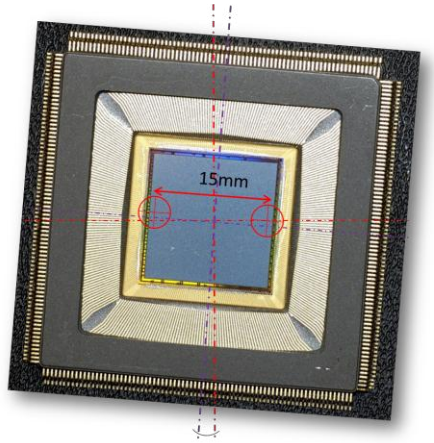


Figure 3 Representation of the possible ASIC alignment error (θ) which translate in a systematic error on the polarization angle knowledge.

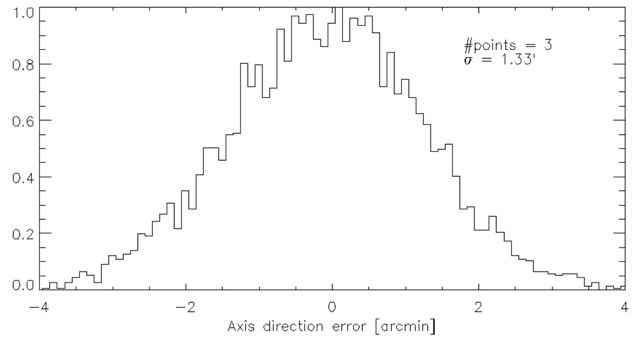
In order to define the ASIC axes orientation and the CS_{ASIC} origin (placed in the center of the ASIC) the vertex of several hexagonal pads constituting a pixel row (or column) will be measured. Considering a 1-σ error of 4 μm on each measurement (3.1 μm CMM MPE over the ASIC dimensions summed in quadrature to 2.5 μm error due to the dimension of the pixel pad gap to be measured) it is possible to estimate the expected 1-σ error on the determination of the CS_{ASIC} orientation.

In Figure 4 the error on the determination of the CS_{ASIC} orientation is showed as a function of the number of points (i.e. ASIC pads) measured. The error distributions have been obtained by means of Monte Carlo simulations (5000 independent measurements, random orientation of CS_{ASIC} with respect to CS_{CMM}). A 1-σ error of 0.26 arcminutes can be obtained by measuring the vertex position of one every two pads (150 pixels out of 300).

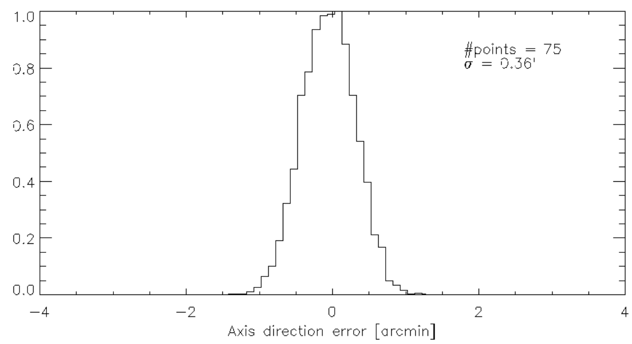
3. DETECTOR REFERENCE COORDINATE SYSTEM

By using the CMM, the ASIC reference coordinate system (CS_{ASIC}) will be optically referred to the detector unit coordinate system (CS_{DU}) defined by three removable bull’s eye targets (e.g. model 717-B manufactured by Brunson Instrument Company, as shown in Figure 5) which will be mounted on the detector mechanical interface by means of three precisely machined holes. These targets will be accessible for measurement during the instrument calibration and integration activities, thus ensuring a direct check of the DU alignment throughout all the project phases.

During the instrument integration and alignment at satellite level, the bull's eye targets will be substituted with spherically mounted retro-reflectors (SMRs), thus allowing for DU-MMA alignment by means of a laser tracker. The different reference point offset between bull’s eye and SMR targets will be software compensated during the metrological measurements.



(a)



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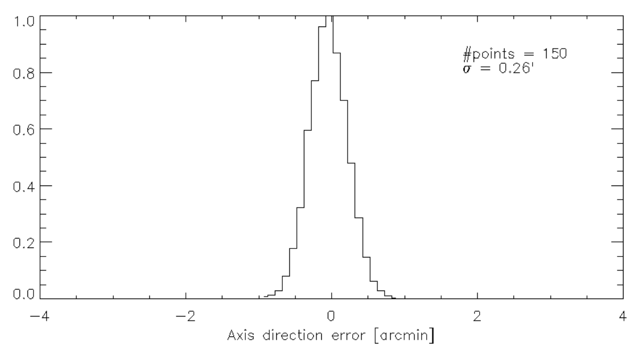

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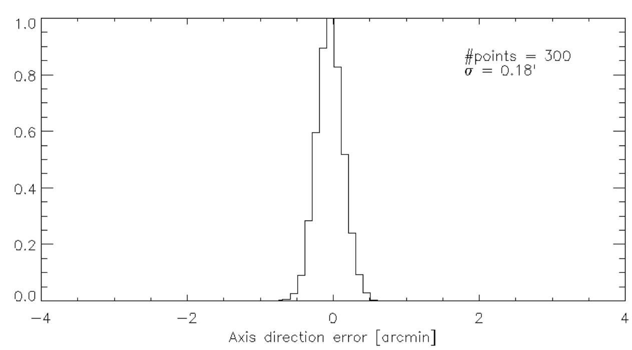

(d)

Figure 4 Distribution of the errors on the determination of the ASIC coordinate system (CS_{ASIC})orientation as a function of the number of ASIC pad measured (from top to bottom: 3, 75, 150 and 300 pads measured). See text for more details.

The estimated accuracy on the determination of the CS_{ASIC} origin is <100 μm (3-σ), while the overall accuracy on the knowledge of the ASIC orientation (i.e. the systematic error on the knowledge of the polarization angle) is estimated to be lower than 4 arcminutes (3-σ) with respect to the S/C Fixed Frame.

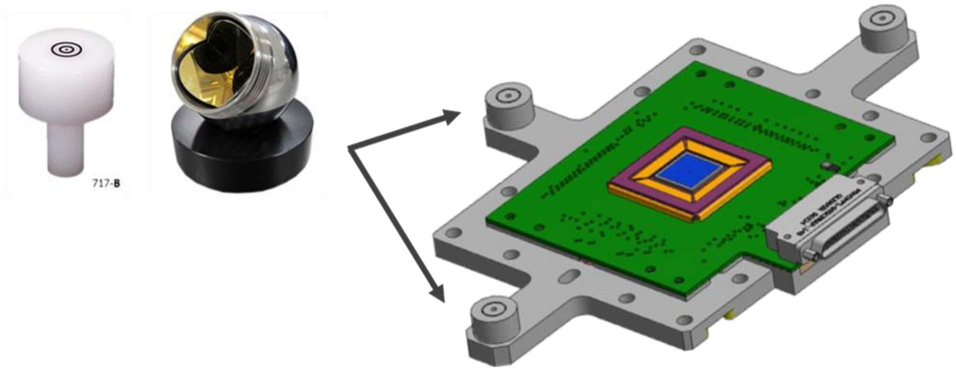

Figure 5 IXPE GPD mechanical interface accommodating the ASIC hybrid and the three removable optical targets (bull's eye or spherically mounted retro-reflectors).

4. VERIFICATION OF THE POLARIZATION ANGLE KNOWLEDGE

The verification of the polarization angle knowledge will be performed during the detector unit on-ground calibrations carried out at the INAF-IAPS X-ray facility[5]. The polarization plane of the X-ray beam produced with a compact Bragg diffraction based polarized source[6] will be characterized by means of a combination of X-ray and optical measurements, carried out in advance, and then referred to three fiducial markers placed on the source external surface. Preliminary measurements show that the expected accuracy on the knowledge of the X-ray polarization plane orientation is better than 2 arcminutes.

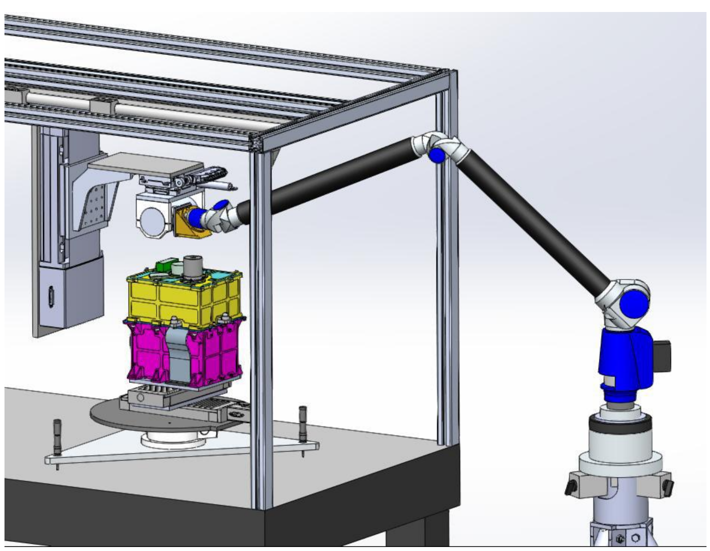

Figure 6 Absolute arm used to refer the polarization plane produced by a Bragg diffraction based polarized source (in orange) to the DU reference system.

An absolute arm (Figure 6) will be used to refer the detector unit orientation to the 100% polarized X-ray source and the metrological measurements will be then compared to the experimentally determined polarization angle to ensure a proper knowledge of the GPD ASIC orientation in the space.

5. CONCLUSIONS

The on-ground characterization of the polarization angle knowledge is mandatory to fulfil the IXPE scientific requirement on the PA accuracy (better than 0.2° at instrument level) and poses strict constraints on both the Detector Unit mechanical design and the metrological procedure used for such a characterization. We elaborated a detailed procedure based on the combined use of vision metrology, touch-trigger probes and optical (laser tracker) measurements that will allow the calibration of the GPD polarization angle knowledge at 4 arcminutes level (3-σ), thus ensuring the fulfilment of the mission requirement.
Moreover, as described in Section 4, an X-ray based verification strategy has been developed at the INAF-IAPS laboratories and will be carried out during the DU on-ground calibration activities planned to start in late 2018.

ACKNOWLEDGMENTS

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