IXPE Instrument Calibration

Calibration of IXPE focal plane detectors

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The IXPE focal plane polarimeters I

- IXPE Detector Unit (DU) are based on the Gas Pixel Detector (GPD)
  - Developed by INFN-Pisa and INAF-IAPS since 2001
  - Main Italian hardware contribution to the mission
- Response is the image of the path of the photoelectron in the gas
The IXPE focal plane polarimeters II

- Emission direction statistically related to the polarization of absorbed photons
- All the characteristics of the photons (direction, time of arrival, energy and polarization) are measured contemporaneously and photon by photon

Response to **polarized** radiation

Response to **unpolarized** radiation

Spectrum at 5.9 keV
Instrument Calibration
DUs are calibrated at INAF-IAPS in Rome (Italy)
- 3x Flight Models are delivered directly to Ball for integration
- Spare DU (and spare MMA) are calibrated jointly at NASA-MSFC

DU calibration possible also with on-board calibration sources
The IXPE Instrument calibration I

- Nominally, 40 days for each of the 4 DUs
- \( \sim 80\% \) of time dedicated to polarized and unpolarized response
  - Requirement on knowledge of the response <0.1%
  - Required custom sources and procedures
- Following satellite dithering strategy, deeper calibration at the center of the field of view

Full illumination

Deeper illumination in the center
Other calibrations:
- Absolute quantum efficiency
- Pixel-to-pixel equalization
- Gain disuniformities
- Energy resolution
- Dead time
- Spatial resolution
- Response to inclined beam

Started on 26th July 2019, last measurement on the spare on 14th September 2020
- Source set-up and alignment during working hours, 7 days per week
- Data acquisition round the clock with remote monitoring
- 530 measurements, 4052.3 hr acquisition and 2.250 billion counts collect
Small facility (yet versatile and dedicated to IXPE)

- Operating in air
  - Air absorption reduced with helium flowing along photon path
- Motorized and manual stages for source and beam-to-detector alignment
- Alignment with a measurement arm
  - Positioning $\approx 10 \ \mu m$
  - Inclination $\approx 1$ arcmin
- Spots from $\sim 25 \ \mu m$
- Commercial SDD spectrometer and CDD for source testing
The Instrument Calibration Equipment II

IXPE clean room @ INAF-IAPS in November 2019
Response to unpolarized radiation

- Most time-consuming measurement
  - $10^5$ cts/mm$^2$ over the entire field of view of $\sim 225$ mm$^2$
  - $10^6$ cts/mm$^2$ on the central $\sim 33$ mm$^2$ region
  - 6 energies

- Unpolarized sources were based on commercial X-ray tubes or $^{55}$Fe
  - Either direct or fluorescence
  - Filters to have a spectrum largely dominated by photons at the same energy

- Often a genuine source polarization is still present depending on
  - bremsstrahlung continuum
  - X-ray tube geometry
  - Diffraction on fluorescence target
Two measurements to separate it from the detector response to unpolarized radiation

Source and spurious contribution sum differently for the two measurements
Map of spurious modulation at 2.7 keV for DU-FM2

Calibration will be applied in the pipeline running at SOC
Response to polarized radiation

- Requirement is to collect $10^4$ cts/mm$^2$ over the entire field of view
- Polarized sources based on Bragg diffraction at nearly 45°
  - Truly monochromatic photons
  - Degree of polarization derived by Bragg angle
  - Different crystals to diffract photons at different energies
- Up to five polarization angles for each energy

Spectrum with ICE test spectrometer
Response to polarized radiation II

Modulation factor as a function of energy, constant over the field of view

Modulation factor as a function of polarization angle, before and after calibration for the spurious modulation
Quantum efficiency

- Comparison with flux measured with a reference detector
  - Measured with monochromatic sources at 5 energies
  - Globally, absolute uncertainty $\sim 1\%$

- Independent estimates with other techniques
  - Beam incident at known angle and imaging capabilities of the GPD
  - Relative quantum efficiency measurement with a reference source

- Measured value lower than expected
  - Now understood to be an effect of adsorption in the GPD gas cell
  - Internal pressure decreasing with time
  - Asymptotic value achieved by the launch

- Little impact on overall sensitivity
Pixel equalization

- By-product of polarimetric response calibration
- Gain of each of the $300 \times 352$ pixels equalized with respect to others
- Rely on the peculiar read-out scheme of the GPD

Pixel-by-pixel equalization map

Relative equalization of single pixels
Gain calibration

- Gain changes with illumination (Charging effect)
- Effect has been modelled
- Removed in the pipeline
Other results I

Energy resolution as a function of energy

Requirement = 25% at 5.9 keV

Spatial resolution at different energies, polarized and unpolarized
Dead time as a function of energy

- Transparency of gray filter included in DU’s FCW
- Provide flux calibration for exceptionally bright sources
On-board calibration sources
DU Filter and Calibration Wheel

- open position for normal observations
- 1 “gray” filter for observation of exceptionally bright sources
- closed position for background measurements
- 4x sources included in each DU
  - Used for monitoring performance, on-ground and in-flight
### On-board calibration sources

<table>
<thead>
<tr>
<th>Cal</th>
<th>Emission</th>
<th>$^{55}$Fe activity [mCi]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>polarized X-rays at 3.0 and 5.9 keV</td>
<td>100</td>
<td>Diffraction at $\sim 38^{\circ}$</td>
</tr>
<tr>
<td>B</td>
<td>unpolarized spot at 5.9 keV</td>
<td>20</td>
<td>Response to unpolarized radiation</td>
</tr>
<tr>
<td>C</td>
<td>unpolarized flat field at 5.9 keV</td>
<td>0.5</td>
<td>Gain calibration</td>
</tr>
<tr>
<td>D</td>
<td>unpolarized flat field at 1.7 keV</td>
<td>100</td>
<td>Gain calibration, Response to unpolarized radiation</td>
</tr>
</tbody>
</table>

Fabio Muleri et al. IXPE Instrument Calibration: On-board calibration sources
On-board calibration sources II

Cal A at 3.0 and 5.9 keV

Cal B, C and D
Conclusions

- IXPE Instrument underwent an extensive on-ground calibration
  - ~80% of time dedicated to measurements specific to IXPE
- Calibration will be monitored in-flight with on-board sources

Lessons learned:
- Calibration in-house was instrumental for successfully accomplishing the task
- Versatility allowed for adapting measurements to the peculiar needs of the detector
- The use of the second facility (ACE) allowed to recover delays in the schedule
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Thank you for your attention!