Accounting for systematic uncertainties in the Imaging X-ray Polarimetry Explorer (IXPE) detector response

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Abstract: *Launched on December 9, 2021, the Imaging X-ray Polarimetry Explorer (IXPE) is the first imaging polarimeter ever flown providing sensitivity in the 2–8 keV energy range, and during the 2-year prime phase of the mission will sample tens of X-ray sources among different source classes. While most of the measurements will be statistics-limited, for some of the brightest objects observed and long integration times, the systematic uncertainties in the detector response (primarily the effective area, the modulation factor and the absolute energy scale) will be important.*

In this contribution, we describe a framework to propagate on high-level observables (e.g., spectro-polarimetric fit parameters) the systematic uncertainties connected with the response of the detector, that we estimate from the relevant ground calibrations and from observations of celestial point sources.

Introduction

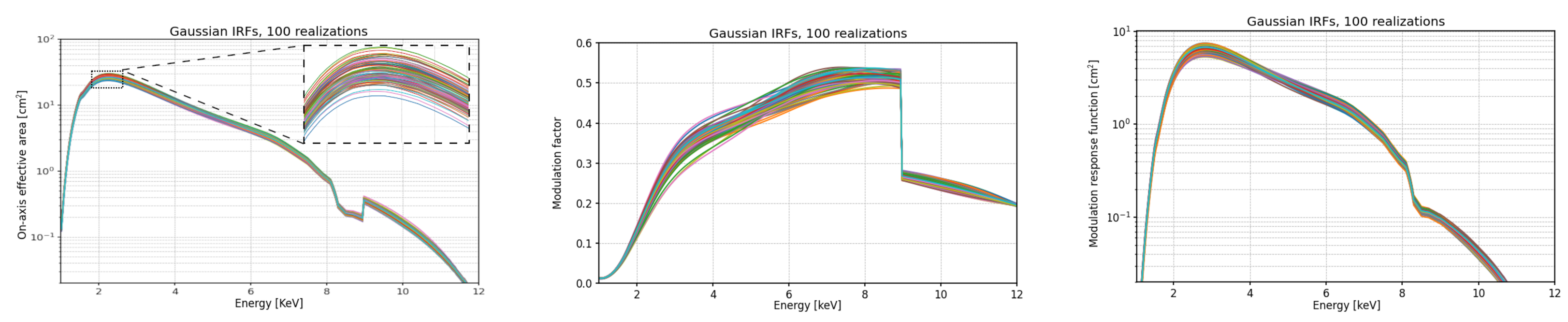
IXPE consists in three identical independent telescopes each comprising a WOLTER-1 type mirror focusing on a Detector Unit (DU) unit composed by gas pixel detector (GPD), a Gas Electron Multiplier (GEM), and is read out by an ASIC. The absorption of a photon in the gas mixture of the DU leads to the emission of a photoelectron which generates an avalanche, whose direction depends on the polarization of the incident photon. By reconstructing the impact point, the initial direction of the photoelectron and its energy, IXPE is capable of imaging spectropolarimetric measurements.

All of these measurements however, are affected by systematics which need to be properly modeled and addressed. Here, we analyze the effect on observables of such systematics, namely:

1. The on-axis effective area, which models the efficiency in the detection of an event as a function of the energy.
2. The modulation factor, which models the efficiency of the reconstruction of the photoelectron direction.
3. The modulation response function which is the efficiency in detecting a polarized event.

Perturbation technique

In order to estimate the effect of uncertainties in the calibration, e set of synthetic response functions are generated as follows: first, a lattice of points is laid out in the energy range, then a random normal value with a σ defined by the uncertainty on the response function at the prescribed energy is assigned to each of these points creating $f(E)$, finally, $f(E)$ is smoothed out across the energy interval with a spline and multiplied by the original response function. The effective area and modulation factor are generated in this way, and the modulation response function is generated by multiplying the first two and propagating the error consistently.

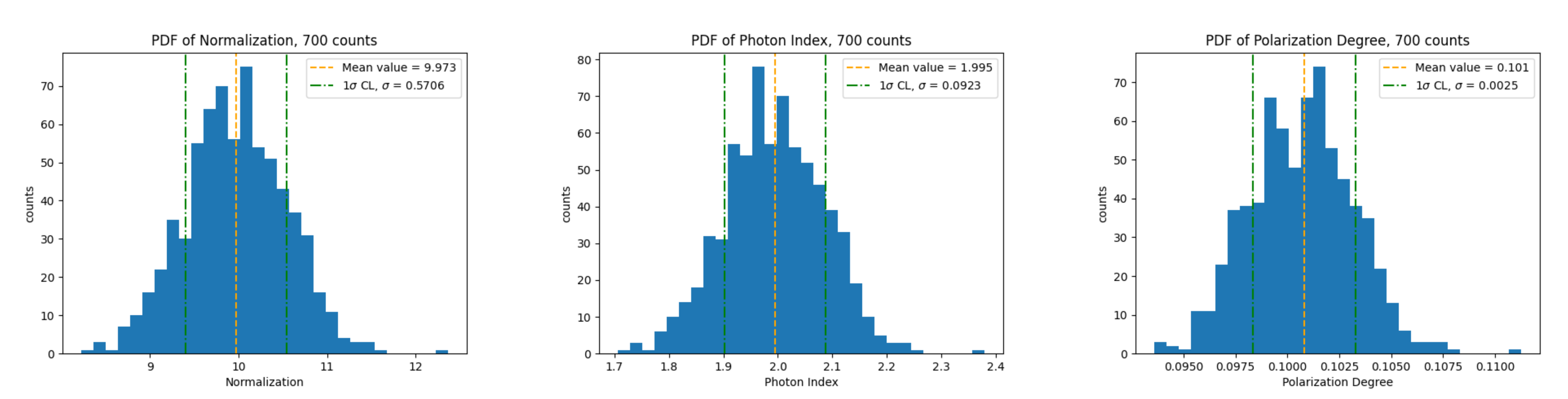


We generate 1k of these synthetic response functions (of which we see a subsample here) to test out the error induced in parameter estimation by assuming unperturbed response functions, thus simulating systematic errors.

Effects of perturbations of the energy scale

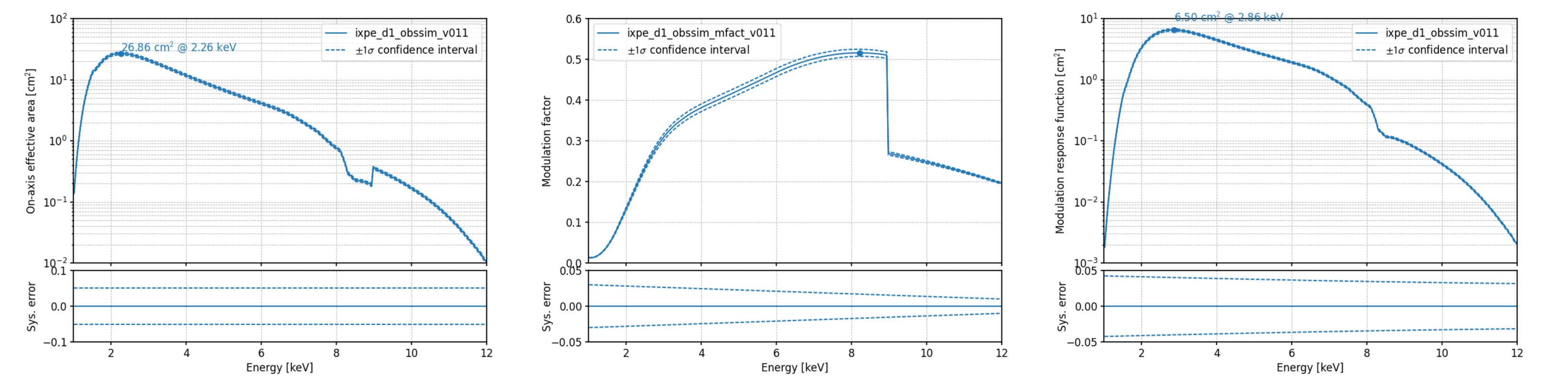
The observable connected to the energy of a recorded event in a level 2 IXPE data file is not the energy itself, but a so-called Pulse Invariant (PI), defined in the OGIP standard. The true physical energy comes from the number of pairs produced in the avalanche generated by the primary photoelectron, but the avalanche is amplified by the GEM before being read out and converted in PIs. The information about the energy of the incident photon is recovered by applying an energy scale conversion that accounts for the gain of the GEM which is not necessarily stable in time, potentially introducing a systematic which is referred to as charging.

Charging alters the gain of the detector in the cas of an exceptionally high rate of events: the generated avalanche ends up depositing charge in the GEM holes, and the local electric field is temporarily changed. This effect has then been simulated by taking the PI column and by perturbing the energy scale with a random gaussian fluctuation with a $\sigma = 0.02$. The resulting output parameter distributions are shown.



Response functions

The three response functions that we will be studying are already included in the response files in the CALDB. Despite accurate calibration, their shape cannot be perfectly known due to uncertainties and here they and modeled with an uncertainty that depends on the energy.



Effective area — Modulation factor — Modulation response function

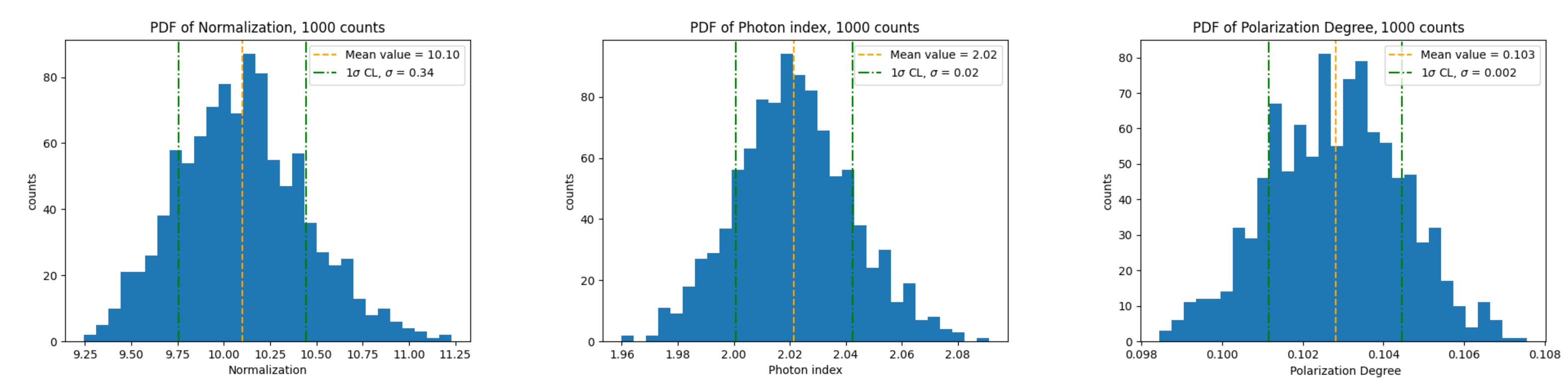
We will assume this uncertainty to be the standard deviation of a probability distribution function at a given energy, that will be used to generate a set of different synthetic response funcions on which to test the effect of a slightly different-than-expected response functions on the inferred parameters.

Effects of perturbations of response functions

The synthetic set of response functions has been used to fold the simulated observation of a point source and the distribution of the parameters inferred with the original response functions are shown, highlighting the effect of systematic with respect of statistical error.

Parameter	Target	Result
Photon index	2	2.000 ± 0.001
Normalization	10	10.00 ± 0.01
Pol. degree	0.1	0.098 ± 0.0015

Simulation target parameters and statistical error ($5{\cdot}10^{6}$ events)



The expected importance of systematics

The effect of systematics of the order of 5% on the response functions on the inferred parameters has been estimated.

- The most influenced parameters are the normalization and the photon index, which largely dominate the statistical error in the case of 5 million events
- The error induced by systematics on the energy scale is even more relevant
- The error in the polarization degree is much less relevant (and this is good news for a polarimeter!)
- 5 million events are a lot for IXPE, comparable to what we expect for the planned observation of the Crab nebula (and probably 10 times brighter than most of other observations), so it's probably safe to assume a few things:

1. The polarization degree won't be affected by systematics, even when charging effects are observed
2. The normalization and Photon index will be more affected by systematics, but at least in the case of the energy scale these effects are probably overestimated since the charging effect is local and dithering could help.