IXPE
CalDB & End User Software

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Overview

The goal of this presentation is to inform the IXPE User Community about:

- IXPE-specific CALDB and HEASoft FTOOL packages released through the HEASARC
- Weighting Schemes implemented in Level 2 Event Lists (see also S. Ehlert's talk)
- Proposal Tools w/features unique to IXPE (e.g. MDP in WebPIMMS, see also S. Ehlert's talk)

Top-level reference URLs:

- IXPE Calibration database https://heasarc.gsfc.nasa.gov/docs/ixpe/caldb/
- IXPE-specific FTOOLS https://heasarc.gsfc.nasa.gov/lheasoft/ftools/headas/ixpe.html
- IXPE Documentation https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/
- IXPE Helpdesk https://heasarc.gsfc.nasa.gov/cgi-bin/Feedback?selected=ixpe

A note on data file naming conventions

File naming convention for ObsID, e.g., 01004701

```
ixpe01004701_det1_evt1_v02.fits
ixpe01004701_det1_evt2_v01.fits
(hk) ixpe01004701_det1_att_v01.fits
(hk) ixpe01004701_det1_gti_v01.fits
```

similar for `det2` and `det3`

And for a segmented observation, e.g., 02001399

```
ixpe02001301_det1_evt1_v01.fits
ixpe02001302_det1_evt1_v01.fits
ixpe02001399_det1_evt2_v02.fits
(hk) ixpe02001301_det1_att_v01.fits
(hk) ixpe02001302_det1_att_v01.fits
(hk) ixpe02001301_det1_gti_v01.fits
(hk) ixpe02001302_det1_gti_v01.fits
```

L1 has segments with ObsIDs ending in 01, 02,…

L2 has one ObsID ending in 99

In this presentation, I will use, e.g., `_evt2_` to denote these archival files generically

Calibration Database

Overview of major IXPE CALDB updates at ~6 month cadence

2022-05-13

- initial release

2022-11-17

- added response files for SIMPLE weighting, updated thermal shield contributions to effective area, added support for ‘boom drift’ model, updated alignment file

2023-06-16

- added response files for gray filter (all three weighting schemes and all three detectors)

2024-02-28

- updated mirror effective area, gray filter transmission, time-dependent quantum efficiency and modulation factor for each detector

2024-xx-xx

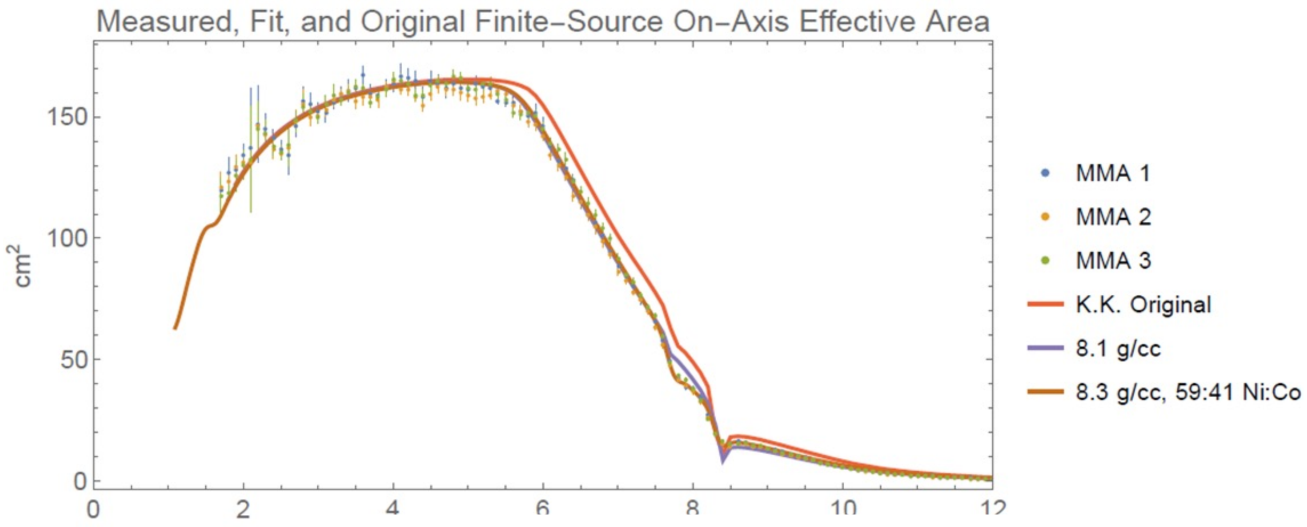
- next release will update boom drift correction model parameters and to account for switching between the two star-tracker optical heads

Calibration Database

2024-02-28

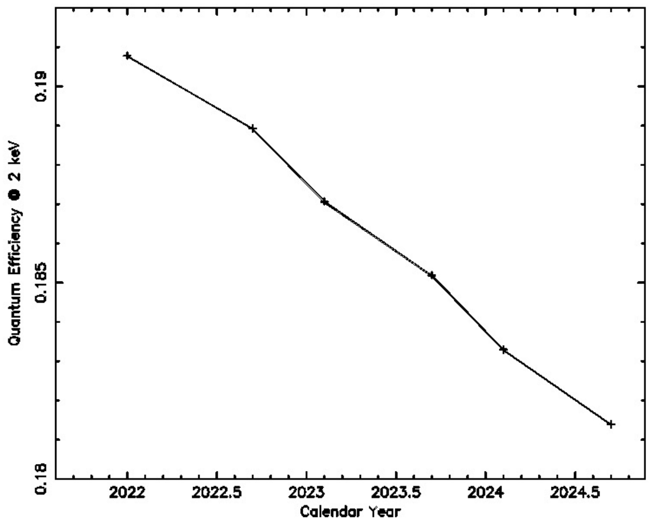
- updated mirror effective area

  Re-evaluated ground calibration data models by adjusting mirror surface density and Ni:Co ratio. Significantly improves Effective Area above 6 keV.



- time-dependent detector quantum efficiency

  Applied detector gas pressure evolution to calculation of time-dependent detector quantum efficiency (6-month updates) and modulation factor. Small but measurable at lowest energies.



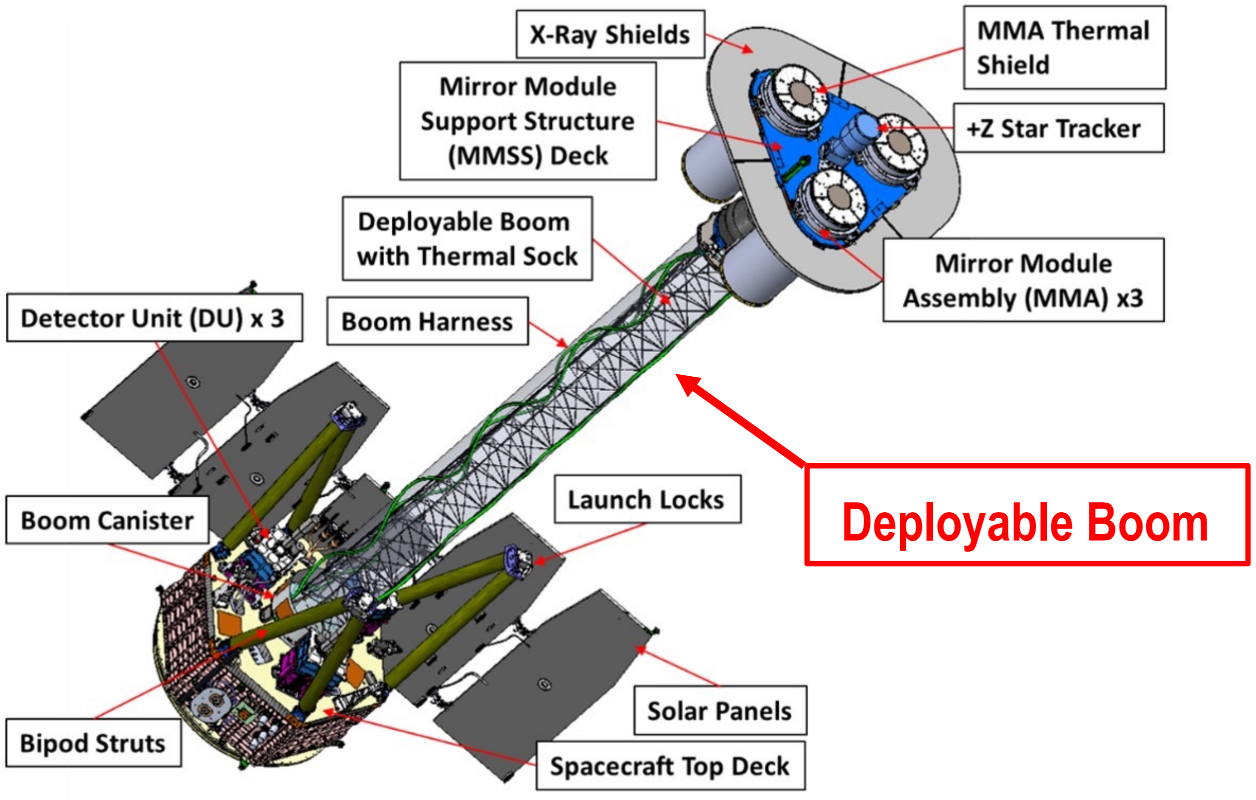
2022-11-17

- added support for ‘boom drift’ model, updated alignment file

Next Release

- further updates to ‘boom drift’ model parameters and star-tracker alignment offsets

Thermal distortions of the IXPE boom during each orbit causes position offsets of the target on the detector. This is modeled by an IXPE task with boom drift model fit parameters added to the CalDB



Calibration Database: Instrument Response Files

The CALDB now contains all three Redistribution Matrix File (RMF) versions for the three choices of weights: SIMPLE, NEFF, and UNWEIGHTED, for each of the three Detector Units (see slides 15-17 for details on event weighting):

	DU1	DU2	DU3
SIMPLE	ixpe_d1_alpha075simple_02.rmf	ixpe_d2_alpha075simple_02.rmf	ixpe_d3_alpha075simple_02.rmf
NEFF	ixpe_d1_alpha075_02.rmf	ixpe_d2_alpha075_02.rmf	ixpe_d3_alpha075_02.rmf
UNWEIGHTED	ixpe_d1_02.rmf	ixpe_d2_02.rmf	ixpe_d3_02.rmf

IXPE – specific FTOOLS

Two flavors: Standalone and Processing Pipeline Modules

IXPE Specific Tasks:

https://heasarc.gsfc.nasa.gov/lheasoft/ftools/headas/ixpe.html

ixpeadjmod	- Remove spurious modulation of IXPE event files
ixpeaspcorr (Python)	- Correct for residual aspect errors
ixpecalcfov (Python)	- Calculate a map of the nominal sky FOV for each detector
ixpecalcarf (Python)	- Corrects an on-axis ARF or MRF file for off-axis vignetting and extraction radius
ixpecalcstokes	- Calculate the Stokes parameters of IXPE event files
ixpedet2j2000 (Python)	- Transform event positions & Stokes parameters from detector to sky coordinates
ixpechrgcorr (Python)	- Apply the charging correction for IXPE event files
ixpeeventviewer (Python)	- Display images of raw event tracks with the event barycenter, absorption point, and initial electron direction overlaid
ixpeevtrecon	- Reconstruct events of IXPE event files
ixpeexpmap (Python)	- Create an exposure map from aspect solution data
ixpegaincorrpkmap	- Calculate PI column values of IXPE event files
ixpegaincorrtemp	- Calculate PHA_T column values of IXPE event files
ixpeinterptemp (Python)	- Fills temperature data gaps in an IXPE Level 1 DU housekeeping file using linear interpolation over gaps less than a g maximum duration
ixpemkevt2gti (Python)	- Combines event, housekeeping, and attitude time intervals into the GTI for Level 2 Event files
ixpeplot_polarization (Python)	- Plots Stokes parameters and MDP99 from ixpepolarization output
ixpepolarization (Python)	- Calculate Stokes parameters for a user-defined region
ixpeweights	- Calculate event-by-event weights of IXPE event files
ixpeversion	- Report IXPE software version

IXPE – specific FTOOLS

ixpecalcarf builds an ancillary response file (ARF) or modulation response file (MRF) based on the most up-to-date on-axis response files (with time-dependent QE), CalDB radial encircled-energy file (applied based on user-specified source extraction region definition), CalDB vignetting data and dither information from the Level 1 attitude data file. Basically, ***ixpecalcarf*** corrects the on-axis response for off-axis vignetting and source region size. ***ixpecalcarf*** is a versatile tool that replaces earlier CALDB releases that provided only on-axis responses regardless of source location relative to the optical axis:

```
ixpecalcarf evtfile=_evt2_ attfile=_att_ resptype=mrf,arf
radius=1.0 weight=0,1,2 arfout=
```

where `radius` is size of source extraction region and `weight` 0,1,2 means UNWEIGHTED, NEFF, and SIMPLE weighting scheme. The output will be an XSPEC-ready FITS file (arf for Stokes I and mrf for Stokes Q and U spectra)

IXPE – specific FTOOLS

ixpepolarization computes the overall Stokes Q and U values over a user-defined sky region, energy range, and time interval and produces a FITS file containing Q, U, and their standard errors, the net polarization degree, polarization angle, modulation factor, and minimum detectable polarization at 99% confidence (MDP99). It also produces a ds9-compatible region file that indicates polarization degree and angle.

```
ixpepolarization infile1=_evt2_ regfile=ds9.reg pi_lo=2.0
pi_hi=8.0 modfact1=- weight_scheme=neff outfile=outfilename
```

where `modfact1=-` is the default (indicates use the CalDB) and `weight_scheme` is UNWEIGHTED, NEFF, or SIMPLE. ***ixpepolarization*** can take up to 3 infiles (infile1, infile2, and infile3) and their corresponding modfact1, modfact2, and modfact3 for the 3 IXPE telescopes. . ***ixpepolarization*** is based on the PCUBE algorithm, part of the **ixpeobssim** suite of applications.

IXPE – specific FTOOLS

ixpeexpmap creates an exposure map in the J2000 tangent plane given a Level 1 attitude housekeeping file and a corresponding GTI file for an observation or observation segment. The resulting exposure map units are sky pixels with values at each coordinate given by the exposure time in seconds. ***ixpeexpmap*** accounts for bad pixels. Exposure maps for multiple detectors can be co-added as differences in orientation and offset due to relative telescope pointing are accounted for.

```
ixpeexpmap infile=_att_ gti=_gti_ outfile=expmap.fits
```

Where the attitude and gti files are located in the housekeeping (hk) DIRECTORY. (It is recommended users obtain only necessary files and not the entire directory contents.)

IXPE – specific FTOOLS

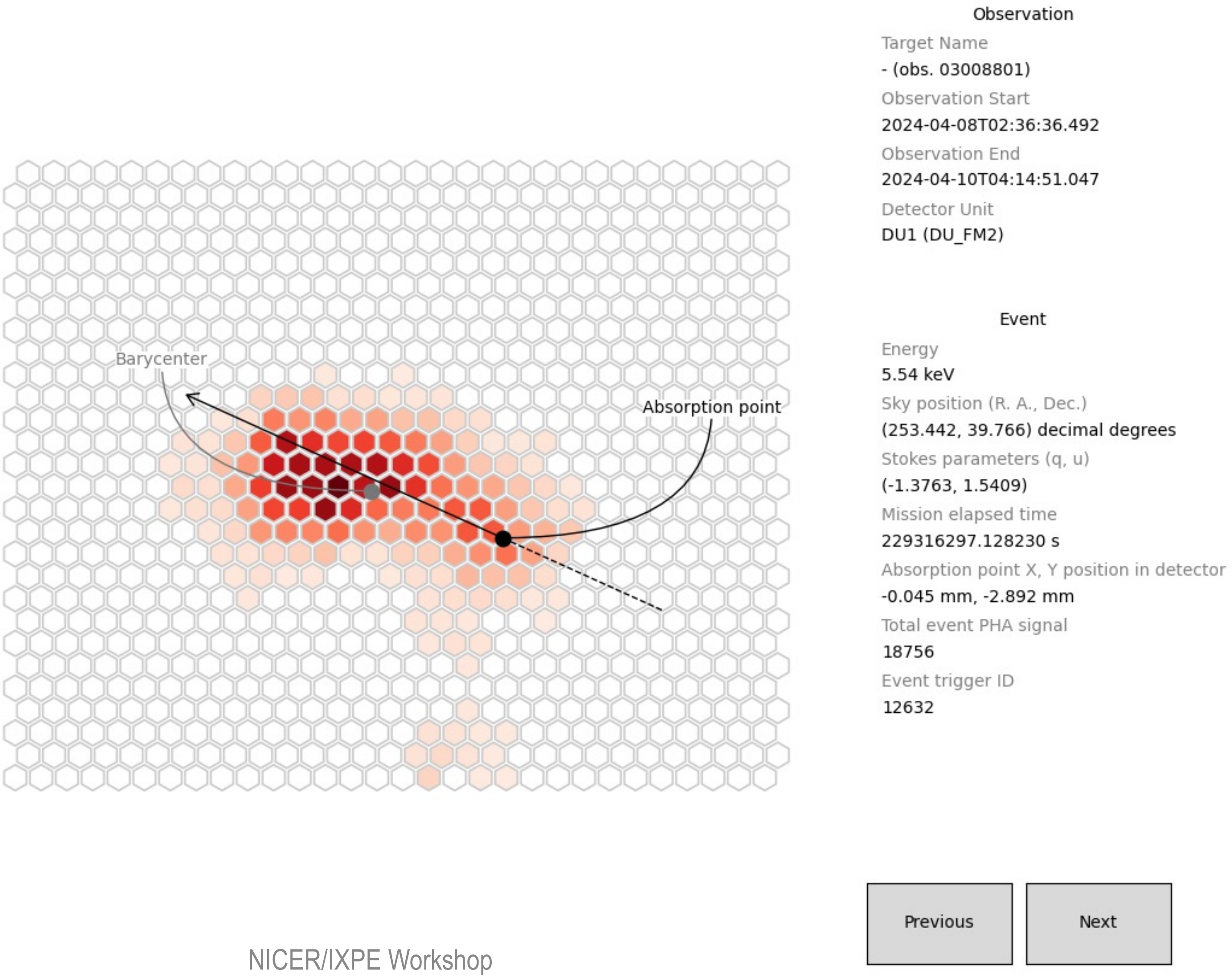
ixpeeventviewer displays 2-D images of raw event electron tracks with the event barycenter, absorption point, and initial electron direction (as deduced by the moments analysis) overlaid. The electron tracks are contained in the Level 1 event files. If a corresponding Level 2 event file name is also given, then ixpeeventviewer will display only events which are present in both event lists. That is, events that are culled by the pipeline processing, for whatever reason, are excluded.

```
ixpeeventviewer evt1list=_evt1_ [evt2list=_evt2_]
```

There are numerous additional display parameters and parameters controlling the moments analysis calculations. Note, however, the IXPE instrument team has optimized these parameters for flight data processing. ***ixpeeventviewer*** is based on *xpevtdisplay*, part of the **ixpeobssim** suite of applications.

IXPE – specific FTOOLS

Note: ***ixpeeventviewer*** will be updated in the next HEASoft release in order to accommodate updated matplotlib and GTK libraries.



IXPE – specific FTOOLS

filter_background.py is a stand-alone python tool that identifies and, optionally, removes charged-particle events from IXPE Level 2 event lists. It is available through the IXPE contributed software page, https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/contributed.html

```
filter_background.py _evt2_ _evt1_ --output rej
```

Note both a Level 2 and a corresponding Level 1 event list file are required inputs. The default output type, `rej`, produces a new Level 2 file with only source events included. `--output bkg` only includes events identified as background and `--output tag` simply adds a new column to the Level 2 file with row values 1 or 0 for identifying 'source' or 'background', respectively, for each event.

Please see A. Di Marco's talk this afternoon and
Di Marco, A. et al. 2023, Handling the Background in IXPE Polarimetric Data, AJ 165, 143

IXPE – specific FTOOLS

ixpeflagbgd is a new module to be added to the IXPE FTOOLS suite in the next HEASoft release. It performs the same filtering as ***filter_background.py*** with `--output tag`.

It has recently been included in the IXPE pipeline processing. End-users can thus use the following command to select only source events from a Level 2 file that contains the header keyword XPFLGBGD = T

```
ftselect _evt2_ filtered_evt2.fits status.eq.bxxxxxxx0xxxxxxxx
```

Weighting in Level 2 Event Lists

- IXPE cleaned, gain-corrected, and aspect-corrected (i.e., Level 2) event lists contain the usual columns **TIME**, **PI** (**P**ulse **I**nvariant energy), and **X**, **Y** sky locations (with conventional WCS keywords included) with one row for each event.
- IXPE Level 2 event lists also contain columns of Stokes parameters: **I= W_MOM**, **Q**, and **U**
- **W_MOM** is the event weight defined as

$$\mathbf{W\_MOM} = ((\mathbf{TL}-\mathbf{TW})/(\mathbf{TL}+\mathbf{TW}))^{0.75} = \mathbf{w}_k$$

where $\mathbf{w}_k$ is the weight of the kth event and **TL** and **TW** are the electron Track Length and Width, respectively such that as the width → 0, W_MOM → 1 and for disk-like tracks, W_MOM → 0.

- The optimal IXPE event weighting is derived in

Di Marco, A. et al. 2022, A Weighted Analysis to Improve the X-Ray Polarization Sensitivity of IXPE, AJ, 163, 170.

Weighting in Level 2 Event Lists

Sum over all events in the j^{th} bin (energy bin, time bin, etc):

$$I_j = \mathcal{E}\sum_{k=1}^{N_j} w_k = \mathcal{E}\sum_{k=1}^{N_j} \mathtt{W\_MOM}_k \qquad Q_j = \mathcal{E}\sum_{k=1}^{N_j} w_k \mathtt{Q}_k \qquad U_j = \mathcal{E}\sum_{k=1}^{N_j} w_k \mathtt{U}_k$$

NEFF (Baldini+22) $\mathcal{E} = (1/T)(\sum_{k=1}^{N} w_k / \sum_{k=1}^{N} (w_k)^2) \equiv (1/TI)N_{\text{eff}}$

SIMPLE (Kislat+15) $\mathcal{E} = 1/T$

UNWEIGHTED $\mathcal{E} = 1/T$ $w_k \equiv 1$

- Baldini, L., et al. 2022, ixpeobssim: A simulation and analysis framework for the imaging X-ray polarimetry explorer. SoftwareX 19, 101194
- Kislat, F., et al. 2015, Analyzing the data from X-ray polarimeters with Stokes parameters. Aph, 68, 45

Extracting Weighted Data with Xselect

Can use ***xselect*** to extract the data (spectra, light curves, etc.)

https://heasarc.gsfc.nasa.gov/lheasoft/ftools/xselect/xsel.html

```
> xselect prefix=mrk501
xsel> read event "./ixpe01004701_det1_evt2_v01.fits.gz"
xsel> filter region "src.reg"
xsel> extract SPEC stokes=NEFF
xsel> save spec ixpe_det1_src_
```

Saves 3 spectral FITS files:

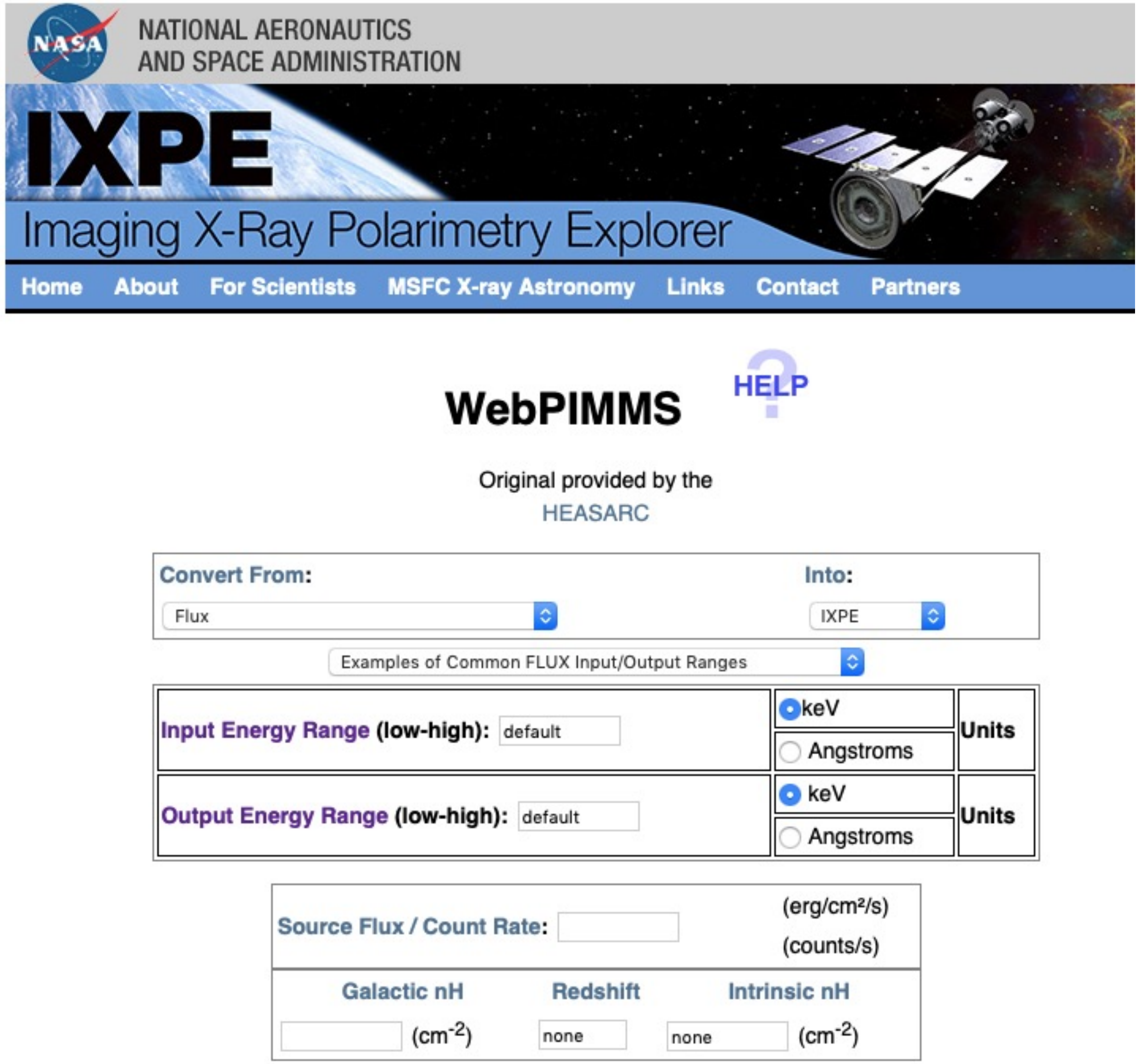
```
ixpe_det1_src_I.pha
ixpe_det1_src_Q.pha
ixpe_det1_src_U.pha
```

Repeat for all DUs, similar commands for other filters

`stokes` takes one of 4 values:

```
xsel> extract SPEC stokes=NEFF
xsel> extract SPEC stokes=SIMPLE
xsel> extract SPEC stokes=UNWEIGHTED
xsel> extract SPEC stokes=NONE
```

WebPIMMS



https://ixpe.msfc.nasa.gov/cgi-aft/w3pimms/w3pimms.pl

Recommend reading the introduction to PIMMS on the MSFC IXPE site

Standard PIMMS interface for selecting:

- Convert From/To (e.g., Flux to IXPE count rate)
- I/O Energy Range
- Source Model parameters (Power Law, Blackbody, etc.)

WebPIMMS

IXPE Output from PIMMS

Input Parameters:

Model #1: **Power Law**
Model #2: **n/a**
Model #3: **n/a**
Model #4: **n/a**

P_I/keV #1: **2.05**
P_I/keV #2:
P_I/keV #3:
Galactic n_H: 2.4E21 cm^{-2}
Intrinsic n_H: 0.0 / / cm^{-2}

Redshift: 0.0
From: flux 1.0E-11 $ergs/cm^2/s$ 0.3-10.0
Input Flux energy range: 0.3-10.0 keV
Internal model normalization = 2.645E-03

Useful mission related information may be found at:
https://ixpe.msfc.nasa.gov/for_scientists/pimms/

IXPE

PIMMS predicts 7.562E-02 cps with IXPE
The above is the total count rate.
The effective count rate for polarization is 0.0631
and the modulated count rate is 0.0138
for a modulation factor of 0.2190
Now estimating 99% confindence level minimum detectable polarization
(MDP_99) as a function of exposure time
In 10000.0 s, MDP_99 = 78.05%
In 100000.0 s, MDP_99 = 24.68%
MDP_99 scales as the inverse of the square root of the integration time.

https://ixpe.msfc.nasa.gov/cgi-aft/w3pimms/w3pimms.pl

Converting from Flux to IXPE count rate returns total, effective, and modulated count rates based on NEFF weighting

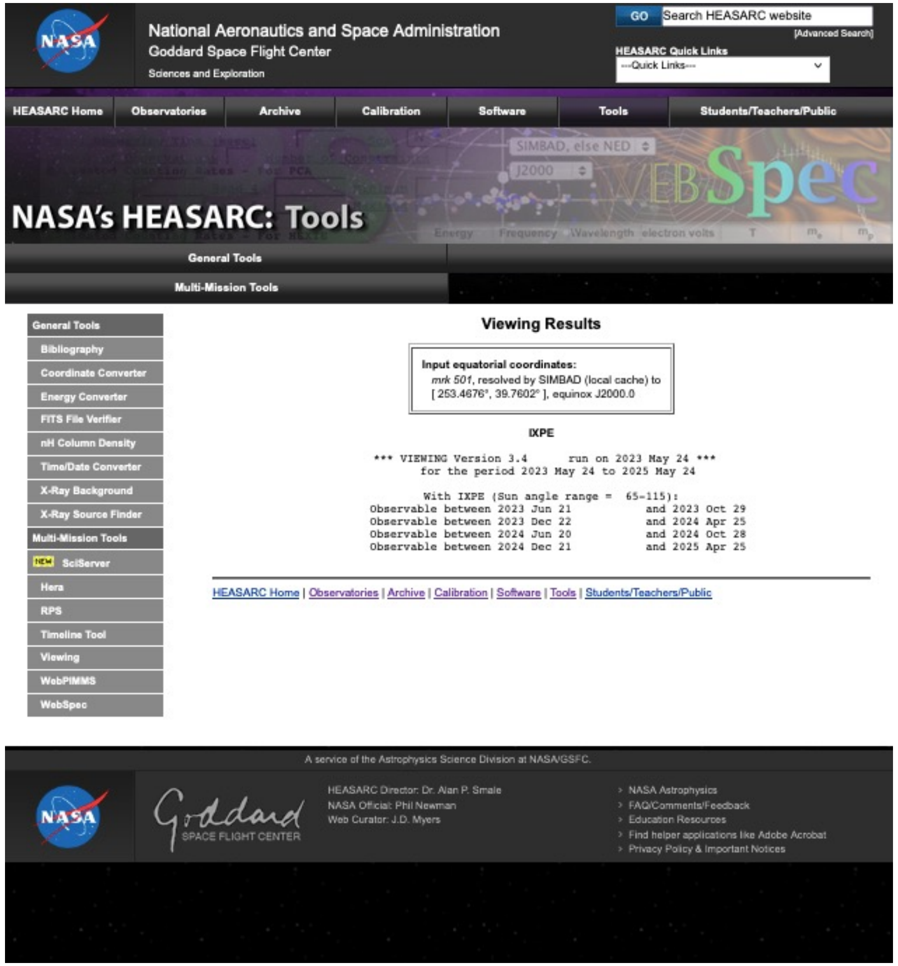
Also returns modulation factor and MDP_99, the 99% confidence level minimum detectable polarization, for a 10,000 s and for a 100,000 s observation.

- ✦ MDP_99 scales as 1/sqrt(T_exposure)
- ✦ Should use 2-8 keV energy range for MDP_99 sensitivity
- ✦ Should use 0.5-10 keV for total count rate estimate

$$\mathrm{MDP}_{99} = \frac{4.29}{\langle\mu\rangle C_S}\left[\frac{C_S + C_B}{T}\right]^{1/2} \approx \frac{4.29}{\langle\mu\rangle\sqrt{N}}$$

e.g., Weisskopf, Elsner, O'Dell 2010

Viewing



https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/viewing/viewing.pl

Simple Input:

1. Select Mission (IXPE)
2. Select Object Name or Coordinates

Output:

1. Returns list of all observable windows start/end dates (year, month, day)
2. Returns results for 1 year period beginning on day of query

IXPE Documentation

- Available at the IXPE Analysis page, includes "official" documentation on the observatory, software, data formats, and other useful information that is updated occasionally
  https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/

Documents	Release Date	Description
Quick Start Guide	March 2024	Information to enable basic scientific analysis of IXPE data, updated to include use of ixpecalcarf.
IXPE Observatory	June 2022	The IXPE Team description of the observatory and guide for users.
IXPE Data Formats	June 2022	The IXPE Team description of the data formats for level 1, level 2, and calibration data products.
IXPE Software User Guide	March 2022	Software analysis guide including a description of the pipeline as well as help for each tool (pdf)
IXPE Instrument	June 2022	The IXPE Team description of the instrument.
Statistics Guide	September 2022	Recommended practices for statistical treatment of IXPE results.