IXPE	Ver. 2.1
The Imaging X-ray Polarimeter Explorer Quick Start Data Analysis Guide	Mar 2025

Quick Start Data Analysis Guide

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Abstract

This document describes the Imaging X-ray Polarimeter Explorer as an aid to potential observers to propose, conduct and analyze science observations from IXPE.

Revision History

Revision	Author	Date	Change
Ver. 1.0	IXPE GOF	03 May 2023	Initial Release
Ver. 2.0	IXPE GOF	09 Feb 2024	added *ixpecalcarf*
Ver. 2.1	IXPE GOF	04 Mar 2025	various updates

Contents

1 What is IXPE

The IXPE (Imaging X-ray Polarimetry Explorer) observatory is a NASA Small Explorer mission, in collaboration with the Italian Space Agency (ASI), providing polarimetric imaging and spectral capabilities in the $2-8$ keV energy range [1]. IXPE was launched on 2021 Dec 9 into a 600-km-altitude, nearly equatorial, 96.6-minute-period circular orbit. Its 2-year baseline science mission began 2022 Jan 11 after a brief commissioning and calibration phase. IXPE began its General Observer (GO) program 2024 Feb 03. All baseline mission science data are publicly available through NASA's High Energy Astrophysics Science Archive Research Center (HEASARC). GO program science data may have up to a six-month proprietary period from the time the data is first available to an observation's Principal Investigator.

The purpose of this document is to help the science community to perform basic spectro-polarization analysis of IXPE observations using publicly-available tools, to navigate the IXPE data archive and calibration database (CALDB), and to assess technical feasibility when preparing proposals through the GO program.
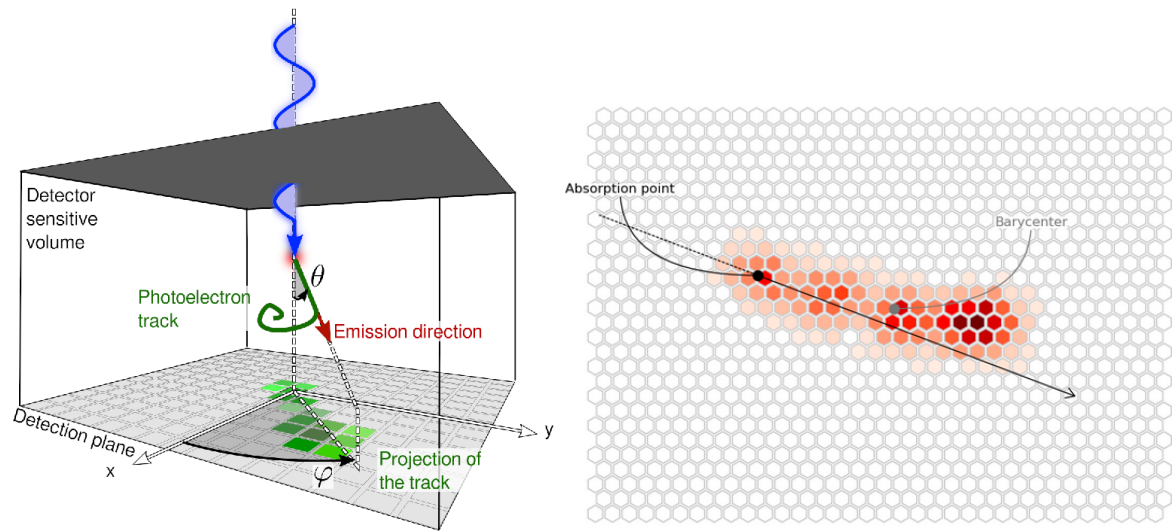

Figure 1: *Left:* Schematic describing how IXPE measures the location and polarization direction, ψ, of a photoelectrically-absorbed photon by imaging the track of the photoelectron emitted within the sensitive volume of the detector. *Right:* Example image of a photoelectron track.

1.1 What does IXPE Measure

IXPE consists of three identical, co-aligned, focusing X-ray mirror assembly−detector pairs (aka telescopes), separated and aligned by a boom deployed during commissioning, that simultaneously observe astrophysical targets. IXPE detects X-rays in the energy range $2-8$ keV through photoelectric absorption in a gas. The energy, location, and time of arrival of each detected event is registered providing spectrometry, imaging, and timing measurements for an ensemble of events. In addition, IXPE works on the principle that photoionization results in an (inner shell) electron emitted preferentially parallel to the direction of the electric field vector, i.e., the polarization direction, of the incident X-ray photon (Figure 1). Specifically, the photoelectron angular distribution is modulated $\propto \cos^2(\psi - \psi_0)$ where ψ is the photoelectron ejection azimuthal angle and ψ_0 is the incident X-ray electric field vector (which is itself perpendicular to the incident photon direction of motion).

IXPE detectors are similar to classic proportional counters in that they use a gas medium to absorb incident X-rays and an applied voltage to cause the resulting electron charge cloud to drift toward an anode readout. However, IXPE's novel design [2] includes a Gas Electron Multiplier, to provide charge gain while preserving the track shape, and a finely pixellated anode (a custom ASIC readout) to *image* the photoelectron track in the readout plane perpendicular to the incident X-ray direction. The shape

of, and charge distribution in, these photoelectron tracks are analyzed in ground processing to determine the location and initial photoelectron direction of each event [3,4].

1.2   How Does IXPE Operate

Given an astrophysical target to observe, IXPE nominally executes a small circular dither pattern as it points toward the object and continues in this orientation until an observation segment is complete. Very bright targets may require two or more segments separated in time to allow stored data to be telemetered. Targets can be observed continuously for a minimum duration of $\sim$57 min each orbit depending on the target's declination. Science observations pause during Earth occultations of the target (and during brief passages through the South Atlantic Anomaly). The IXPE solar panels are fixed perpendicular to the primary axis of the observatory and must point within 34° of the Sun; thus, target visibility is generally restricted to an $\sim$70-day window twice per year.

The IXPE science program begins with a set of celestial targets and durations of observations (at a minimum). The Science Operations Center (SOC) at NASA/MSFC then turns these into scheduled programs of spacecraft actions to be executed by the Mission Operations Center (MOC) at the Laboratory for Atmospheric and Space Physics (LASP) of the University of Colorado (under contract to BAE, formerly Ball Aerospace, the IXPE spacecraft manufacturer). The MOC sends commands to, and receives data from, the observatory primarily through the ASI-provided ground station at Malindi, Kenya, with a backup station in the Republic of Singapore. The SOC then ensures the resulting data are fully recovered, processed, and validated. This processing includes, among other things, event track reconstruction and parameterization,detector gain corrections to event energies, and telescope boom motion corrections to event sky positions. The processed data are delivered to the High Energy Astrophysics Science Archive Research Center (HEASARC) at NASA/GSFC where they are made available to the science community.

1.3   What are IXPE's Performance Parameters

Table 1 lists several IXPE physical parameters of interest to end-users. The three 15×15 mm^2 IXPE focal plane detector units (DUs) are clocked 120° from each other to help reduce any detector-correlated residual effects remaining after removing known systematic effects on polarization sensitivity. With telescope focal lengths of $\sim$4000 mm, the plate scale is approximately 1 mm = 51.6″. The pixel size is 50 μm or 2.6″. Full, official descriptions of the IXPE observatory and instrumentation are available on the MSFC IXPE website as the User Guides IXPE-SOC-DOC-011A_UG-Observatory.pdf and IXPE-SOC-DOC-008A_UG-Instrument.pdf respectively.

Table 1: IXPE System Performance.

Mirror Angular Resolution	$\leq 30''$ HPD
Effective Field of View	$12.9' \times 12.9'$ (300 pixel $\times$300 pixel)
Operational Energy Range	$2-8$ keV
Energy Resolution	0.57 keV at 2 keV ($\propto \sqrt{E}$)
Timing	100 μs absolute time accuracy

IXPE is sensitive to photons up to $\sim$10 keV. However, the modulation response drops steeply below 2 keV due to the near-circularity of the photoelectron tracks and the quantum efficiency of the detectors (and the effective area of the mirror assemblies) decrease significantly above 8 keV. Therefore, the recommended or operational IXPE energy range is $2-8$ keV.

2 How Do I Plan Science Observations with IXPE

There are publicly-available tools for estimating source counting rates, polarization sensitivity, and target accessibility that can aid IXPE observation planning. There are also on-line listings of targets observed in the past and targets planned to be observed in the near future. These tools are briefly introduced here with more details in the following subsections.

- PIMMS, the Portable Interactive Multi-Mission Simulator, is a widely used tool for estimating source count rates for high-energy observatories. For IXPE, PIMMS also calculates the sensitivity to polarization (§2.2). A version of PIMMS for IXPE is also maintained at the IXPE site at MSFC.

- *viewing* is a simple on-line tool that can be used to determine when an astronomical position or target can be viewed by IXPE.

- The IXPE Long Term Plan and As-Run Target List are available on-line; see also §3. These lists can be useful to check if your favorite source will be or has been observed by IXPE. Note that some objects have been observed several times and/or their observation has been segmented.

In addition to the functionality of *Xselect* for IXPE data reduction and *XSPEC* for spectro-photometric analysis, as described in §4 and §6, respectively, *ixpeobssim* is a publicly-available, Python-based, simulation and analysis framework developed for IXPE [5]. *ixpeobssim* is designed to produce simulated observation products in the same form and format as standard IXPE event lists. The interested reader is encouraged to consult the extensive documentation and examples available through the *ixpeobssim* website.

2.1 What is Minimal Detectable Polarization

IXPE's unique contribution to high-energy astrophysics is its ability to determine the net polarization angle, ψ, (also called the position angle) of an X-ray source and the degree of polarization, Π, (also called the polarization fraction; sometimes expressed as a percentage). The standard sensitivity metric for X-ray polarimetry is the Minimum Detectable Polarization at 99% confidence level, MDP_{99}, defined (e.g., [6]) as:

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

where C_S and C_B are the source and background count rates, T is the observation exposure time and $\langle\mu\rangle$ is the source-count-weighted modulation factor. The rightmost expression holds when $C_S \gg C_B$ and the total number of detected counts $N \to C_S \times T$. The modulation factor is the amplitude of the $\cos^2$ distribution of the photoelectron (azimuthal) ejection directions from a 100% polarized source as measured by an instrument (while the position angle corresponds to the angle of the distribution peak). Optimal sensitivity to polarization is achieved when $\langle\mu\rangle \to 1$. In general, and for the IXPE detectors specifically, $\langle\mu\rangle$ is a function of energy (see also Fig. 3, §5).

The MDP_{99} is the smallest polarization fraction that can be measured at a 99% confidence level. Eq. 1 shows that measuring polarization requires a large number of events: To measure, say, an MDP_{99} of 1% for a nominal value $\mu = 0.5$ and in the absence of background requires 736,000 counts. For most astronomical sources, then, measurements of polarization will require long observations. A graphic depiction of attainable MDP_{99} for various power law spectra against source flux in the IXPE $2-8$ keV operational band is shown in Fig. 2.

2.2 How Do I Estimate Polarization Sensitivity Using PIMMS

For IXPE, PIMMS returns the estimated MDP_{99} levels, or the exposure time necessary to reach a desired MDP_{99} level, in addition to the IXPE counting rate given a spectral model and source flux (or count rate from any of many other X-ray missions) over a user-prescribed energy range. The gray filter can be prescribed for bright sources. Specifically, PIMMS returns the total (three telescopes combined) source count rate, C_S, that can be used to calculate the sensitivity to variations in the source energy spectrum
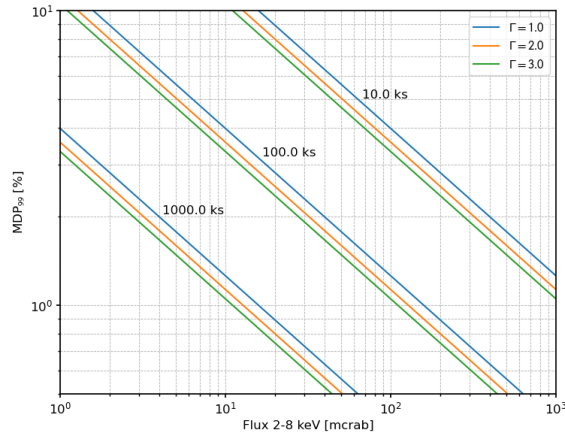
Figure 2: Lines at constant observing time in the MDP_{99} vs. flux space, for simple power-law spectra with different indices, Γ. One mCrab in the 2-8 keV range is $\sim 2.1 \times 10^{-11}$ erg cm^{-2} s^{-1}

or light curve. PIMMS also returns the *effective* count rate, C_E, and the *modulated* count rate, C_M, defined such that the modulation factor over the output energy range is $\langle \mu \rangle = C_M / C_E$.

Analysis shows a statistically better measure of the polarization can be made by weighting events by how well polarization can be measured (§4.1). Therefore, PIMMS uses C_E, defined as the sum of the weighted counts per unit time, instead of C_S for computing MDP_{99} from Eq. 1.

For IXPE, PIMMS calculates MDP_{99} for a 10 ks and a 100 ks observation. The MDP_{99} for any other integration time, T can then be calculated by scaling by $1/\sqrt{T}$ (see Eq. 1). Alternatively, PIMMS accepts a user-defined MDP_{99} level (as a percentage) and returns the exposure time needed to reach that value for the given input model.

PIMMS assumes source polarization properties are independent of energy. This may not be true for many astrophysical sources of interest and PIMMS may need to be queried for carefully-selected output energy ranges. In particular, the default output PIMMS energy range for IXPE is $0.5-10$ keV which is most useful for estimating the total source count rate that must be telemetered. The operational energy range, $2-8$ keV, should be used to estimate the IXPE sensitivity to polarization. Also, many astrophysical sources may have both a non-thermal (potentially polarized) spectral component and an unpolarized thermal or emission line component. For planning purposes, the 3-6 or 4-6 keV energy range may be appropriate, for example, if a non-thermal continuum between potentially strong thermal emission lines of Si and Fe is expected.

As always, PIMMS does not account for spectral energy broadening, source variability, nor vignetting (decrease in the energy-dependent effective area with off-axis angle) but assumes a steady, on-axis, point-like source. Thus PIMMS should be used with care (and rarely alone) when preparing proposals for spectrally-complex, extended, or time-variable sources.

3   How Do I Get Archived IXPE Data Products

The IXPE data archive is maintained by the High Energy Astrophysics Science Archive (HEASARC) at the GSFC. Unless noted otherwise, all data files are in the Flexible Image Transport System (FITS) format and follow all the relevant FITS standards and conventions. The IXPE Master Catalog, is a database table of all IXPE observations archived at the HEASARC. To display the catalog,

1. Select the 'Browse this table...' link in the upper left corner of the Master Catalog page to access the search form.

2. Use the default query settings (that is, do *not* put an entry in the 'Object Name or Coordinates' field) to see the complete catalog,

3. Select 'Start Search' at the bottom of the search form.

The search will return the full table of planned and observed targets. Data are publicly available if the 'public_date' field is set to a time in the past. Data can be retrieved by:

1. Selecting rows (unique Observation Sequence Numbers) of interest from the results table,

2. Selecting desired data from the Data Products list (e.g., IXPE Level 2 Data (ixpe.obs.l2)), and

3. Choosing a retrieval option (e.g., Preview and Retrieve).

Note that a given target may have multiple table entries corresponding to separate observations of the same target. Also note that IXPE data files, especially Level 1 and housekeeping files, can be very large; in general, only the Level 2 data are needed for scientific analysis[1]. Thus, selecting the 'Preview and Retrieve' retrieval option is recommended. This option gives you another chance to view and select precisely what datasets are available (and their size).

Some observations performed early in the mission had some processing issues that are captured in an ascii-formatted README file associated with the archived science data and retrievable using the following sequence:

1. Selecting rows (unique Observation Sequence Numbers) of interest from the results table,

2. Selecting 'IXPE All Data for the Observation (ixpe.obs)' from the Data Products list,

3. Choosing Preview and Retrieve,

4. Clicking on the 'DIRECTORY' link in the 'IXPE All Data for the Observation' in the Preview results table, and

5. selecting the README file (if it exists) in the resulting directory listing.

Users should always check for a README file.

Alternatively, data search and retrieval can start at the main HEASARC Browse search form by entering an object name (or coordinates or time interval), selecting the IXPE mission, and then initiating a search of available archival data. Data can then be selected and retrieved as outlined above.

3.1   What Do The Level 2 Event Lists Contain

The IXPE Level 2 science event data files contain the filtered and calibrated data used for scientific analysis. Level 2 event data file names are of the form ixpe*PPnnnnpp*_det*D*_evt2_v*xx*.fits where *PPnnnnpp* is the eight-digit Observation Sequence Number consisting of a 2-digit mission year identifier, *PP*, a 4-digit target ID, *nnnn*, and a 2-digit segment number, *pp*, all of which are zero-padded. *D* is the detector unit number (1, 2, or 3); and *xx* is a zero-padded 2-digit processing version number. (Typically, only the latest processing version data is available in the archive.)

The IXPE Level 2 binary table EVENTS extension contains the columns listed in Table 2 (in addition to trigger identification and status flags) where TIME is the event timestamp, PI is the calibrated (gain-corrected) "Pulse Invariant" event energy channel (ranging from 0 to 374 corresponding to mid-bin energies from 0.02 keV to 14.98 keV with uniform, 40 eV, binsize), and X and Y are the sky positions converted from the detector coordinate positions to the J2000 tangent plane centered on the targeted pointing (as encapsulated in their associated WCS keywords). W_MOM, Q, and U are the (pseudo-)Stokes parameters for the event (§4.1) used to determine the spectro-polarimetric properties of an ensemble of events. All but the Stokes parameters are standard event table columns commonly used in high energy astronomy.

Table 3 lists several EVENTS extension header keywords of importance. These include MJDREFI and MJDREFF, the integer and fractional parts, respectively, of the Modified Julian Date reference time needed to convert TIME column values to absolute time; LIVETIME, the sum of the valid Good Time

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[1]An observation "attitude" housekeeping file will be needed to build certain instrument response files, see §5.1, and an "orbit" housekeeping file will be needed if barycenter corrections are to be applied.

Table 2: IXPE Level 2 EVENT Extension Table Column Names and Numbers.

No.	Column Name	Format	Units	TLMIN	TLMAX
2	TIME	D	s		
5	PI	J	chan	0	374
6	W_MOM	E			
7	X	E	pixel*	1	600
8	Y	E	pixel*	1	600
9	Q	D			
10	U	D			

*Pixels are $2.6'' \times 2.6''$

Table 3: Selected IXPE Level 2 EVENTS Extension Header Keywords.

Keyword	Sample Value	Keyword Comment
MJDREFI	57754	start mission MJD (integer part)
MJDREFF	0.00080074074074	start mission MJD (fractional part)
DEADAPP	T	Flag indicating if dead time correction has been applied
DEADC	0.921	The ratio of LIVETIME/ONTIME values
LIVETIME	85062.977847	[s] Sum of LIVETIME column for valid GTI
ONTIME	92363.433994	[s] Engineering-defined exposure time
RA_OBJ	83.633040	Right Ascension of target in J2000
DEC_OBJ	22.01449	Declination of target in J2000

Intervals (corrected for deadtime), equivalent to the time on target or exposure time; and the target J2000 coordinates, `RA_OBJ,DEC_OBJ`, in decimal degrees.

A complete listing of all table columns and header keywords for all FITS file extensions for all publicly-released IXPE data files are contained in the official IXPE data formats documentation.

4   How Do I Extract Spectro-polarimetric Data with *Xselect*

The command-line FTOOLS program, *Xselect*, can be used to extract PHA spectra from IXPE Level 2 event lists as detailed below (§4.2). The main HEASoft page contains links to select and download *Xselect* and other general-use FTOOLS software, mission-specific tools for IXPE (also documented in IXPE-SOC-DOC-009D_UG-Software.pdf), and/or the *XANADU* data analysis package containing *XSPEC* as well as detailed installation instructions. See also the online *Xselect* User's Guide.

4.1   How are IXPE Level 2 Events Weighted

IXPE is an imaging spectro-polarimeter that registers individual events. As with other event list data, observers can select (filter) events by energy, celestial coordinates, time, and phase in the usual way. IXPE observers can also apply *weighting* to events extracted from IXPE Level 2 event lists using *Xselect*. Weighting is based on the capability of the electron track characterization algorithm to correctly reconstruct the original photoelectron direction. This capability depends on the morphology of individual tracks; a long straight track terminating in a high surface density charge region (Bragg peak) is more likely to yield a correct photoelectron location and direction than a short track or one suffering a large-angle Coulomb scattering near the initiation point and is assigned a higher weight. IXPE scientists have found [4] the optimal weight, w_k, for the kth event is a power of the ellipticity, α, of its electron

track:

$$w_k = \alpha^{0.75}.$$

IXPE Level 2 data files record this weight in column `W_MOM` along with the Stokes parameters $\mathtt{Q} \equiv 2\cos(2\psi)$ and $\mathtt{U} \equiv 2\sin(2\psi)$ related to the photoelectron ejection angle, ψ, measured, per IAU convention, counterclockwise from celestial North.

The implementation of the weighting method for spectro-polarimetric analysis is as follows. Consider a set of $k_j = 1, \ldots, N_j$ polarization measurements (events) within some energy bin, j, (e.g., as given by the jth `PI` channel). The Stokes parameters for the set of events are defined as:

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

There are two variants of the weighting currently available when extracting IXPE data with *Xselect*: `SIMPLE` weighting following Kislat et al. ([7]) in which case $\mathcal{E} = 1/T$ and `NEFF` weighting, following Baldini et al. ([5]), in which case $\mathcal{E} = (1/T)(\sum_{k=1}^{N} w_k / \sum_{k=1}^{N} (w_k)^2) \equiv (1/TI)N_{\text{eff}}$ where N_{eff} is the effective number of events. Here, T is the observation exposure time. For no weighting, $w_k \equiv 1$ for all k, and the above expressions reduce to the familiar formulae:

$$I_j = \frac{N_j}{T} \qquad Q_j = \frac{1}{T} \sum_{k=1}^{N_j} \mathtt{Q}_k \qquad U_j = \frac{1}{T} \sum_{k=1}^{N_j} \mathtt{U}_k.$$

Appropriate instrument response files are available (or can be constructed) for both `SIMPLE` and `NEFF` weighting and for unweighted data analysis (§5).

Weighting of IXPE events is optional. The IXPE collaboration recommends weighting when performing spectro-polarimetric fits (§6) but not for simple tests for polarization detection (§6.2).

4.2   A Walk Through *Xselect*

Xselect, under HEASoft version 6.30.1 and later, allows users to extract the Stokes I, Q and U spectra from IXPE Level 2 event lists. The IXPE observation of the blazar Mrk 501 obtained in 2022 July, Observation Sequence Number 01004701, will be used as an example. The Level 2 event lists are retrieved from the IXPE archive following the steps outlined in §3 as a single tarfile then extracted onto disk as:

```
> ls -l
 -rw-r--r-- 1 owner  group  3827598 Jul 27 11:07 ixpe01004701_det1_evt2_v01.fits.gz
 -rw-r--r-- 1 owner  group  3781526 Jul 27 11:07 ixpe01004701_det2_evt2_v01.fits.gz
 -rw-r--r-- 1 owner  group  3620924 Jul 27 11:07 ixpe01004701_det3_evt2_v01.fits.gz
```

Given a source and background 'region file' for DU1 generated by, e.g., the data visualization application DS9, here called *src.reg* and *bkg.reg*, respectively,[2] then the *Xselect* steps required to extract the source and background spectra are simply:

```
> 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_
xsel> clear region
xsel> filter region "bkg.reg"
xsel> extract SPEC stokes=NEFF
xsel> save spec ixpe_det1_bkg_
```

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[2]The contents of *src.reg* are the single line `circle(16:53:51.766,+39:45:44.41,60.0")`, and those of *bkg.reg* are the two lines `circle(16:53:51.766,+39:45:44.41,252.0")` and `-circle(16:53:51.766,+39:45:44.41,132.0")`. The standard 60″ source region size corresponds to roughly the 95% encircled energy fraction for an on-axis source.

If a prefix is not specified at the command line, then the user will be prompted for a session name. Also, at startup, the `default_mission` may not be set to IXPE but the `read event` command will recognize the data as IXPE data and prompt the user to reset the mission. The above *Xselect* commands result in six files being generated:

```
> ls -l *.pha
 -rw-r--r-- 1 owner group 63360 date ixpe_det1_src_I.pha
 -rw-r--r-- 1 owner group 63360 date ixpe_det1_src_Q.pha
 -rw-r--r-- 1 owner group 63360 date ixpe_det1_src_U.pha
 -rw-r--r-- 1 owner group 63360 date ixpe_det1_bkg_I.pha
 -rw-r--r-- 1 owner group 63360 date ixpe_det1_bkg_Q.pha
 -rw-r--r-- 1 owner group 63360 date ixpe_det1_bkg_U.pha
```

Note that the data visualization application (specified by, e.g., `pset xselect imagedisp=ds9`) can be spawned within *Xselect* itself with the command

```
xsel> plot image
```

although the region file(s) need to be read in with the `filter region` command within *Xselect* in order to be applied to the event list. Note also that the region filters should either be in WCS or Physical coordinates. Regions created in Image coordinates will not work correctly if image binning is not 1.

The additional "`stokes`" argument supplied to the `extract SPEC` command for IXPE observations can be any one of:

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

These control the applied weighting scheme; NEFF or SIMPLE as described in §4.1 or UNWEIGHTED that sets all the weights to unity, while NONE extracts only the single, unweighted I (counts) spectrum. Similar commands to the above should be executed also for DU2 and DU3.[3]

5   How Do I Get Calibrated Instrument Response Files

Spectro-polarimetric analysis of IXPE data using *XSPEC* requires Instrument Response Files to be associated with each spectrum. Some instrument response files are maintained in the IXPE calibration database (CALDB) system indexed and maintained by the HEASARC and others are generated for specific observation times and sky locations (§5.1). Unless noted otherwise, all CALDB files are in the Flexible Image Transport System (FITS) format and follow all the relevant FITS standards and conventions. The full CALDB should be retrieved from the IXPE calibration database files page or from the CALDB supported-missions page and installed as explained in the general CALDB download and installation instructions.

Specifically, the CALDB contains a set of two Redistribution Matrix Files[4] (RMF) for each Detector Unit: One is intended for use in unweighted data analysis and is assigned a name of the form `ixpe_dD_20170101_VV.rmf` where D is the DU number and VV is the CALDB file version number (20170101 indicates the response file is applicable to data taken after 2017 Jan 01). The other is used when weighting events by either the NEFF or SIMPLE weighting method (§4.1); these have names of the form `ixpe_dD_20170101_alpha075_VV.rmf`. The output from the FTOOL *quzcif* can be used to display the path and filename of the most up-to-date version of the redistribution matrix files. E.g., for DU1:

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[3]In general, the region files could be independently defined for each telescope; in this example, the source location has the same celestial coordinates within 0.25″ for all three detectors so the same region files are used for all three detector units.

[4]The instrument responses are defined on 275 energy bins corresponding to mid-bin energies of 0.02 to 10.98 keV (40 eV bins) whereas there are 375 PI channels; i.e., the RMFs are not square matrices.

```
> quzcif IXPE GPD DU1 - MATRIX now now -
```

currently returns a result of the form:

```
$CALDB/data/ixpe/gpd/cpf/rmf/ixpe_d1_20170101_02.rmf 1
$CALDB/data/ixpe/gpd/cpf/rmf/ixpe_d1_20170101_alpha075_02.rmf 1
```

(with `$CALDB` expanded to the environment variable value).

Spectro-polarimetric analysis of IXPE data also requires an Ancillary Response File (ARF) and a Modulation Response File (MRF) for each DU. MRFs are defined as the product of the energy-dependent modulation factor, $\mu(E)$, and the ARF: $\text{MRF}(E) = \text{ARF}(E) \times \mu(E)$. On-axis versions of these response files are included in the CALDB. However, as of the release of HEASoft version 6.33 (c. 2024 Feb), the mission-specific FTOOL *ixpecalcarf* (§5.1) should be used to generate ARFs and MRFs.
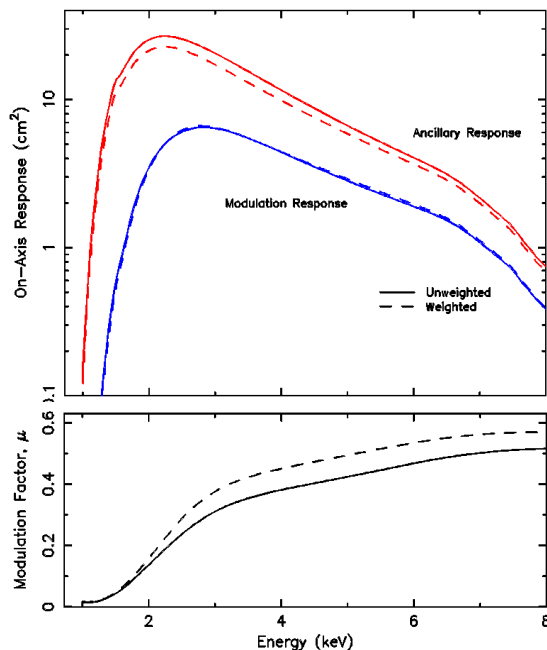

Figure 3: *Top:* On-axis NEFF-weighted and unweighted IXPE ancillary response and modulation response for detector unit DU1.*Bottom:* Corresponding modulation factor, $\mu(E)$.

Figure 3 displays a non-dithered, on-axis, NEFF-weighted ARF and an unweighted ARF for DU1 and the modulation factor for that detector. Note how the modulation factor is increased if events are weighted but that the effective number of events, and hence the system effective area, decreases. The net effect is a greater polarization sensitivity for weighted analysis. PIMMS uses the NEFF weighting to calculate MDP_{99} (§2.2).

The *ixpecalcarf* tool builds an observation-specific ARF or MRF that correctly accounts for off-axis vignetting, a finite source extraction radius, and dither motion. The tool first makes an on-axis response from components stored in the IXPE CALDB. Corrections are then made using additional CALDB data, pointing information from spacecraft attitude housekeeping data, and the observation's time exposure information from the Level 2 event list GTI (good time interval) binary table extension.

5.1 A Walk Through *ixpecalcarf*

It is assumed at this point that Stokes I, Q and U spectra have been extracted from an IXPE Level 2 event list as outlined in §4.2, that the corresponding Level 1 spacecraft attitude data file(s) for the

observation are in hand, and that the IXPE CALDB has been properly installed. Continuing with the observation of the blazar Mrk 501, Observation Sequence Number 01004701, as an example, the following command line generates an MRF for the source Stokes Q spectrum, `ixpe_det1_src_Q.pha`, extracted using *Xselect* from the detector DU1 event list:

```
> ixpecalcarf \
evtfile=ixpe01004701_det1_evt2_v01.fits.gz \
attfiles=ixpe01004701_det1_att_v01.fits.gz \
arfout=ixpe_det1_src_Q.mrf \
specfile=none radius=1.0   weight=1   resptype=mrf
```

Here, as in §4.2, the input Level 2 event list is `evtfile=ixpe01004701_det1_evt2_v01.fits`. The space-craft attitude file, part of the engineering housekeeping file suite retrievable from the "hk" subdirectory in the data archive (§3) is `attfile=ixpe01004701_det1_att_v02.fits.gz`.[5] The resulting Response File is appropriate for an observation in which IXPE has been pointed so that the sky location of the target is at roughly the center of the detector (i.e., along the optical axis), and a 1.0' source extraction region radius (`radius=1.0`), and NEFF weighting method (`weight=1`) have been used to extract the spectrum file. (Other weighting options are `weight=0` for UNWEIGHTED and `weight=2` for SIM-PLE). The name of the output Response File is `arfout=ixpe_det1_src_Q.mrf` and the type of response file is a modulation response file (`resptype=mrf`). Specifying `specfile=none` in this example prevents *ixpecalcarf* from modifying any spectral files.

A similar *ixpecalcarf* command can be used to generate an ARF for Stokes I spectra by setting `resptype=arf`. The Stokes Q MRF can be used for both the Stokes Q and U spectra. Finally, the *ixpecalcarf* tool should be applied similarly for the three DU2 and three DU3 Stokes spectra.

There are several additional *ixpecalcarf* parameters that can be set including other ways of defining the response file type and output filename; it is recommended the user read the full *ixpecalcarf documentation* that is also accessible through the *fhelp* command-line FTOOL utility.

For spectro-polarimetric analysis, each spectrum should be associated with their respective instrument response files. One way to achieve this is to assign the values of the keywords RESPFILE and ANCRFILE the correct instrument response filenames for each Stokes spectrum using the FTOOL *fthedit*. The RESPFILE keyword should point to the appropriate CALDB RMF and the ANCRFILE keyword should be set to the corresponding *ixpecalcarf* output as follows. For the Stokes I spectrum:

```
> fthedit ixpe_det1_src_I.pha keyword=RESPFILE operation=add \
 value=" '$CALDB/data/ixpe/gpd/cpf/rmf/ixpe_d1_20170101_alpha075_02.rmf'" longstring=YES
> fthedit ixpe_det1_src_I.pha keyword=ANCRFILE operation=add \
 value=" 'ixpe_det1_src_I.arf' " longstring=YES
```

The `operation=add` parameter will add the keyword RESPFILE or modify the keyword if it already exists. Note the reference to the environment variable $CALDB. For the Q and U spectra, the RESPFILE is the same as for the I spectrum but the correct ANCRFILE is the Modulated Response File:

```
> fthedit ixpe_det1_src_Q.pha keyword=RESPFILE operation=add \
 value=" '$CALDB/data/ixpe/gpd/cpf/rmf/ixpe_d1_20170101_alpha075_02.rmf'" longstring=YES
> fthedit ixpe_det1_src_Q.pha keyword=ANCRFILE operation=add \
 value=" 'ixpe_det1_src_Q.mrf'" longstring=YES

> fthedit ixpe_det1_src_U.pha keyword=RESPFILE operation=add \
 value=" '$CALDB/data/ixpe/gpd/cpf/rmf/ixpe_d1_20170101_alpha075_02.rmf'" longstring=YES
> fthedit ixpe_det1_src_U.pha keyword=ANCRFILE operation=add \
  value=" 'ixpe_det1_src_Q.mrf'" longstring=YES
```

Of course, PHA file edits similar to the above should be applied also to all spectra corresponding to all three DUs. Note that, in a typical *XSPEC* implementation (§6), properly-scaled background spectra are simply subtracted from the observed spectrum to obtain the source spectrum so that instrument response files do not need to be assigned to background spectra.

---

[5] These input files are expected to be in the local working directory in this example; otherwise, full path names should be given or soft links made. Note also the usage of the backslash line continuation character in this example.

6 How Do I Fit Stokes Spectra with *XSPEC*

The *XANADU* data analysis package containing *XSPEC* is available for download from the main HEA-Soft page. *XSPEC*, version 12.12.1 and later, allows users to analyze the Stokes I, Q and U spectra from IXPE observations.

Having extracted source and background spectra for all three telescopes using *Xselect* according to § 4.2, we now have eighteen PHA files with instrument response files assigned as needed. It is recommended that the spectra are simultaneously fit with the same model but with an overall normalization model parameter allowed to vary between telescopes. Thus, the I, Q, and U set of spectra for each detector are grouped (such that a single set of model fit parameters are applied to all group members):

```
> xspec
xspec> data 1:1 ixpe_det1_src_I.pha
xspec> data 1:2 ixpe_det1_src_Q.pha
xspec> data 1:3 ixpe_det1_src_U.pha

xspec> data 2:4 ixpe_det2_src_I.pha
xspec> data 2:5 ixpe_det2_src_Q.pha
xspec> data 2:6 ixpe_det2_src_U.pha

xspec> data 3:7 ixpe_det3_src_I.pha
xspec> data 3:8 ixpe_det3_src_Q.pha
xspec> data 3:9 ixpe_det3_src_U.pha
```

and backgrounds assigned:[6]

```
xspec> backgrnd 1 ixpe_det1_bkg_I.pha
xspec> backgrnd 2 ixpe_det1_bkg_Q.pha
xspec> backgrnd 3 ixpe_det1_bkg_U.pha

xspec> backgrnd 4 ixpe_det2_bkg_I.pha
xspec> backgrnd 5 ixpe_det2_bkg_Q.pha
xspec> backgrnd 6 ixpe_det2_bkg_U.pha

xspec> backgrnd 7 ixpe_det3_bkg_I.pha
xspec> backgrnd 8 ixpe_det3_bkg_Q.pha
xspec> backgrnd 9 ixpe_det3_bkg_U.pha
```

Note that if the RMF and MRF or ARF files associated with the source spectra are not assigned as in § 5.1 by assigning values to the keywords RESPFILE and ANCRFILE, then they can be assigned within *XSPEC*, e.g.,

```
xspec> arf 1:1 ixpe_det1_src_I.arf
xspec> arf 1:2 ixpe_det1_src_Q.mrf
xspec> resp 1:1 ixpe_d1_20170101_alpha075_02.rmf
xspec> resp 1:2 ixpe_d1_20170101_alpha075_02.rmf
```

etc., where local copies of the instrument response files are assumed.

XSPEC contains several simple multiplicative energy-dependent polarization models. These are

- *polconst* for constant (energy independent) polarization degree and angle,

- *pollin* for polarization with a linear energy dependence, and

- *polpow* for polarization with a powerlaw energy dependence.

---

[6]Note *Xselect* automatically adds a BACKSCAL and an EXPOSURE keyword to extracted spectra so that *XSPEC* can properly normalize the background.

For example, for the constant polarization model used here, there are two fit parameters denoted A, the polarization fraction, and ψ, the polarization angle in degrees, such that the model multiplicative factors are $A\cos(2*\psi_{\mathrm{rad}})$ for the Q spectrum and $A\sin(2*\psi_{\mathrm{rad}})$ for U where ψ_{rad} is ψ in units of radians (and the multiplicative factor is 1.0 for I. The full description of all three multiplicative models are given in the *XSPEC* manual.

The model to be applied to the Mrk 501 spectra is a simple absorbed power law restricted (as per recommendation) to the 2-8 keV energy range.

```
xspec> ignore *:0.0-2.0 8.0-**
xspec> model constant*tbabs(polconst*powerlaw)
```

Note that the multiplicative `polconst` component applies only to the `powerlaw` portion of the model by design. The initial model parameters are set such that Data Group 2 and 3 parameters are tied to those of Data Group 1 with the exception of the `constant` which is allowed to vary for Groups 2 and 3 (== 1 for Group 1). Fitting the model to the data results in:

```
========================================================================
Model constant<1>*TBabs<2>(polconst<3>*powerlaw<4>) Source No.: 1   Active/On
Model Model Component  Parameter  Unit       Value
 par  comp
                         Data group: 1
   1    1    constant   factor                 1.00000      frozen
   2    2    TBabs      nH          10^22      0.646199     +/-  0.103537
   3    3    polconst   A                      7.45137E-02  +/-  1.80681E-02
   4    3    polconst   psi         deg        -47.4491     +/-  6.99991
   5    4    powerlaw   PhoIndex               2.75111      +/-  5.02693E-02
   6    4    powerlaw   norm                   0.106061     +/-  7.93573E-03
                         Data group: 2
   7    1    constant   factor                 0.955110     +/-  9.46462E-03
   8    2    TBabs      nH          10^22      0.646199     = p2
   9    3    polconst   A                      7.45137E-02  = p3
  10    3    polconst   psi         deg        -47.4491     = p4
  11    4    powerlaw   PhoIndex               2.75111      = p5
  12    4    powerlaw   norm                   0.106061     = p6
                         Data group: 3
  13    1    constant   factor                 0.907673     +/-  9.00732E-03
  14    2    TBabs      nH          10^22      0.646199     = p2
  15    3    polconst   A                      7.45137E-02  = p3
  16    3    polconst   psi         deg        -47.4491     = p4
  17    4    powerlaw   PhoIndex               2.75111      = p5
  18    4    powerlaw   norm                   0.106061     = p6
------------------------------------------------------------------------


Fit statistic  : Chi-Squared                  144.82     using 149 bins, spectrum 1, group 1.
                 Chi-Squared                  159.07     using 149 bins, spectrum 2, group 1.
                 Chi-Squared                  119.97     using 149 bins, spectrum 3, group 1.
                 Chi-Squared                  147.30     using 149 bins, spectrum 4, group 2.
                 Chi-Squared                  118.64     using 149 bins, spectrum 5, group 2.
                 Chi-Squared                  147.13     using 149 bins, spectrum 6, group 2.
                 Chi-Squared                  147.98     using 149 bins, spectrum 7, group 3.
                 Chi-Squared                  174.30     using 149 bins, spectrum 8, group 3.
                 Chi-Squared                  154.01     using 149 bins, spectrum 9, group 3.
Total fit statistic                           1313.23    with 1334 d.o.f.
```

```
Test statistic : Chi-Squared                        1313.23      using 1341 bins.
 Null hypothesis probability of 6.52e-01 with 1334 degrees of freedom
```

6.1   How Do I Interpret the *XSPEC* Fit Results

It is advised that IXPE observers and potential proposers become familiar with the recommended practices for statistical treatment of IXPE results as addressed in the memo "Note on IXPE Statistics" [8] and restrict analysis to the χ^2 statistic for parameter estimation.

There are two parameters of interest in our example. These are given by the polarization fraction, A, and polarization angle, ψ, parameters of the polconst component (model parameters 3 and 4 in our example). The *XSPEC* error (or uncertain) command can be used to deduce confidence intervals for these parameters. In particular, the 99% confidence intervals for one parameter of interest are:

```
XSPEC12>error 6.635 3
 Parameter   Confidence Range (6.635)
     3     0.0279905     0.121086    (-0.0465232,0.0465718)
XSPEC12>error 6.635 4
 Parameter   Confidence Range (6.635)
     4      -66.8445     -28.0283    (-19.3953,19.4209)
```

where, e.g., for parameter 3, the output values are the parameter number, the 99% lower and upper limits, and (in parentheses) the lower and upper limits relative to the best fit value $A = 0.0745$ (7.45%). Similarly, the 1-σ uncertainty on parameter 3 is:

```
XSPEC12>error 1.0 3
 Parameter   Confidence Range (1)
     3     0.0564509     0.0925801    (-0.0180629,0.0180664)
```

Of particular interest is the 2-D error contour for the two parameters polarization fraction and polarization angle combined. The following commands can be used to visualize this:

```
XSPEC12> steppar 3 0.00 0.21 41 4 -90 0 36
XSPEC12> plot contour ,,4 1.386, 4.61 9.21 13.81
```

where the first command generates a fit-statistic grid with 41 steps in parameter 3 on the range $0.00-0.21$ and 36 steps in parameter 4 on the range -90 to 0 and the second command draws contours at 50, 90, 99, and 99.9% confidence levels for 2D errors (χ_2^2) as shown in Figure 4.

Note that the detection is deemed "highly probable" (confidence $C > 99.9\%$) as $A/\sigma = 4.123 > \sqrt{-2\ln(1-C)}$ where $\sigma = 0.01807$ as given by *XSPEC* above. Finally, we can use PIMMS to estimate MDP$_{99}$ as in § 2.2. First, use *XSPEC* to determine the (model) flux on the 2-8 keV energy range:

```
XSPEC12> flux 2.0 8.0
Data Group Number: 1
 Model Flux  0.014517 photons (7.9123e-11 ergs/cm^2/s) range (2.0000 - 8.0000 keV)
Data Group Number: 2
 Model Flux  0.013865 photons (7.5571e-11 ergs/cm^2/s) range (2.0000 - 8.0000 keV)
Data Group Number: 3
 Model Flux  0.013176 photons (7.1818e-11 ergs/cm^2/s) range (2.0000 - 8.0000 keV)
```

Then enter the appropriate parameters (power law model with Galactic hydrogen column density $n_{\rm H}/10^{22} = 0.646$, photon index $\Gamma = 2.75$, and flux (average of three detectors) 7.55×10^{-11} erg cm^{-2} s^{-1} in the 2-8 keV range). PIMMS returns MDP$_{99}$ of 5.62% for a 100 ks exposure. Scaling by the actual mean of exposure time of 97243 s gives an MDP$_{99}$ of 5.70% meaning that, for an *unpolarized* source with these physical parameters, an IXPE observation will return a value $A > 0.057$ only 1% of the time. This is consistent with the highly probable detection deduced here of a polarization fraction of $7.45 \pm 1.8\%$.
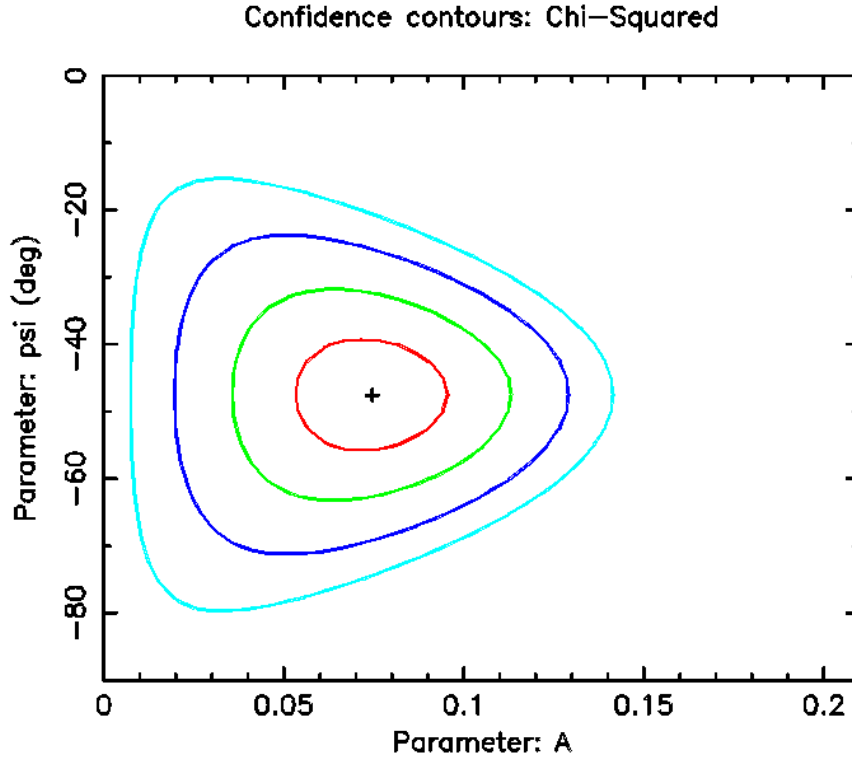
Figure 4: *XSPEC*-generated χ^2 image in (A,ψ) space where A is the polarization fraction and ψ the polarization angle for the blazar Mrk 501 obtained in 2022 July, Observation Sequence Number 01004701, with best fit values (0.0745, -47.45°) at $\chi^2_{1334} = 1313.23$ (denoted by the small cross). Contour levels are shown for confidence levels of 50, 90, 99, and 99.9% for two parameters of interest. Some plotting parameters were modified for added clarity.

6.2   How Should I Use Stokes Parameters

The polarization degree, Π, and polarization angle, ψ, can be estimated directly from the Stokes parameters Q and U. Q and U are independent of one another, unlike Π and ψ. With sufficiently large numbers of events, the central limit theorem ensures Q and U are normally distributed with equal standard deviation, $\sigma_Q = \sigma_U = \sigma$. Consequently, an error contour in the (Q,U) plane is a circle centered on the measured mean values Q_0, U_0. In contrast, the uncertainties for Π and ψ are $\sigma_\Pi = \sigma$ and $\sigma_\psi = \sigma/\Pi$ so that, in cases where there is a non-detection, the polarization angle is unconstrained and, in general, as in Figure 4, error contours are not simple to describe.

Note also that the Stokes parameters are additive so that background events can be simply subtracted from background-plus-source events.

These properties mean one can test for detection significance using a null hypothesis and Q, U, and σ. Assuming the true values are $Q = U = 0$, $\chi^2_2 \equiv (Q^2 + U^2)/\sigma^2$ is distributed as a χ^2 distribution with 2 degrees of freedom.

The FTOOL *ixpepolarization* can be used to calculate the mean and standard deviation of the Stokes Q and U parameters for an (optional) user-defined sky region, time interval, and/or energy range directly from a Level 2 event list file (or a set of files such as for the three DUs). The tool also returns Π, ψ, MDP_{99} and other information for the region (or set of regions). The FTOOL *ixpeplot_polarization* can be used to display the output from *ixpepolarization* as shown in Fig. 5 generated from the commands

```
> ixpepolarization \
infile1=ixpe01004701_det1_evt2_v01.fits \
```

```
infile2=ixpe01004701_det2_evt2_v01.fits \
infile3=ixpe01004701_det3_evt2_v01.fits \
regfile=src.reg pi_lo=50 pi_hi=200 weight_scheme=neff \
outfile=QU_allDUs.fits
> ixpeplot_polarization infile=QU_allDUs.fits
```
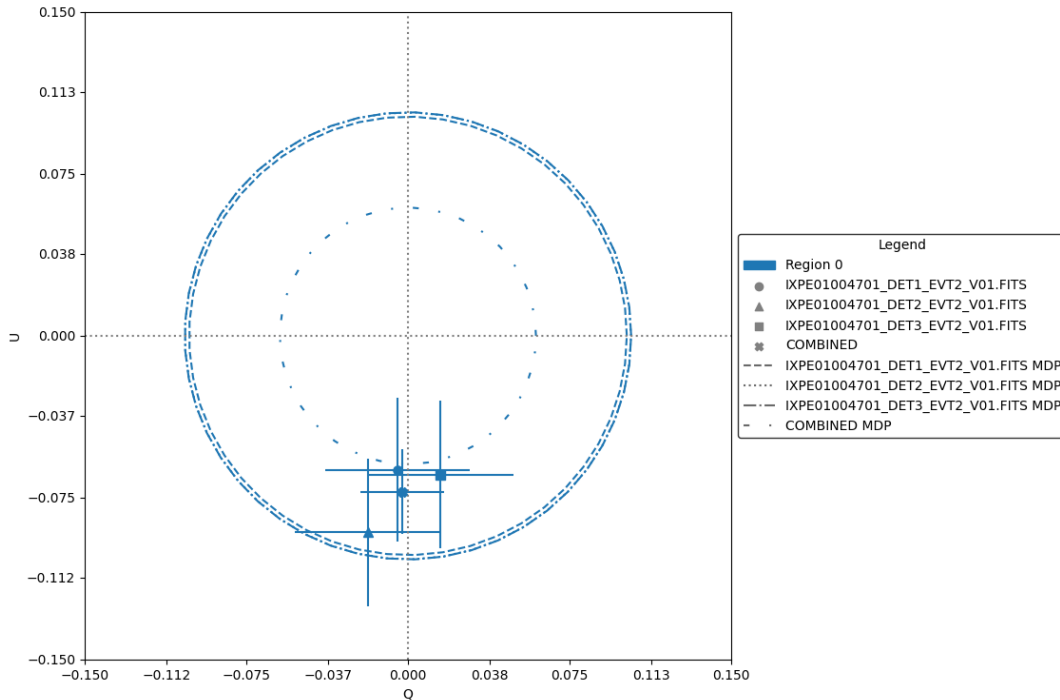

Figure 5:   Screen capture of *ixpeplot_polarization* display of the Q, U plane with the parameter pair means and one-σ standard deviations shown for the individual DUs (circle, triangle, and square symbols) and for all three combined (cross). Also displayed are the individual and combined computed MDP_{99} values, shown as dotted and dot-dashed lines, for the Mrk 501 observation ObsID 01004701. Note that the measurements for individual telescopes are not significant at the 99% confidence level, $\Pi < \mathrm{MDP}_{99}$, but are for the three telescopes combined. The radial position of the combined mean Q and U is $\Pi = \sqrt{Q^2 + U^2} = 0.072$. The angle from the positive Q axis, $-92°$, transforms to 2ψ. Both values are consistent with the spectro-polarimetric fit results of §6.

Note the choice of `weight_scheme=unweighted` (the other choices are `neff` and `simple`). Because the modulation factor and effective area of the telescopes vary strongly with energy, using weights across a large energy band is not recommended for the simple test of Stokes parameter values given by *ixpepolarization*. For spectro-polarimetric fits and small energy bands this is not an issue.

7   References

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[6] Weisskopf, M.C., Elsner, R.F. and O'Dell, S.L. 2010, SPIE, 7732, 77320E

[7] Kislat, F., et al. 2015, AstropartPhys, 68, 45

[8] Ehlert, S., et al. 2022, "Note on IXPE Statistics" memo.