NICER CALIBRATION: FPM Detector and XRC parameters

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Summary and Release History

This document briefly describes NICER detector parameter files provided in CALDB.

- `nixti{pi,pifast}detparamYYYYMMDDvVVV.fits` - NICER FPM detector parameters, such as read-out noise, Fano factors, and low-energy trigger efficiency function parameters, for both the slow (PI) and fast (PI_FAST) read-out chains; used for response matrix (RMF) modeling
- `nixtinoiseparamYYYYMMDDvVVV.fits` - NICER noise peak parameters for the slow (PI) chain only; used for background modeling
- `nixtixrc{align,shell}paramYYYYMMDDvVVV.fits` - NICER XRC (concentrator optic) parameters, including misalignment, throughput and roughness parameters for each shell; used for effective area (ARF) modeling

Detector Response Parameters

Public Release	NICER CALDB Ver	File Name	Comments
2021-07-07	xti20210707	nixtipidetparam20170601v001.fits	PI channel detector parameters
2021-07-07	xti20210707	nixtipifastdetparam20170601v001.fits	PI_FAST channel detector parameters

Detector Noise Parameters

Public Release	NICER CALDB Ver	File Name	Comments
2021-07-07	xti20210707	nixtinoiseparam20170601v001.fits	PI noise parameters

XRC Alignment Parameters

Public Release	NICER CALDB Ver	File Name	Comments
2021-07-07	xti20210707	nixrcalignparam20170601v001.fits	Alignment derived post-launch
2021-07-07	xti20210707	nixrcalignparam20170601v002.fits	Alignment using vignetting profiles as templates (internal use only)
2021-07-07	xti20210707	nixrcalignparam20170601v003.fits	Alignment using vignetting profiles as templates (final release with improved filtering)

XRC Shell Throughput Parameters

Public Release	NICER CALDB Ver	File Name	Comments
2021-07-07	xti20210707	nixrcshellparam20170601v001.fits	Throughput parameters corresponding to xti20200722 ARF release
2021-07-07	xti20210707	nixrcshellparam20170601v002.fits	Throughput parameters using simplified roughness constraints (internal use only)
2021-07-07	xti20210707	nixrcshellparam20170601v003.fits	Throughput parameters determined with alignment parameters v003.

Introduction

The files described in this document describe NICER Focal Plane Module (FPM) and X-Ray Concentrator (XRC) performance parameters.

The NICER observatory payload is composed of 52 individual operating telescopes (56 as-built, and launched with 4 not functioning). Each telescope is composed of a single XRC, which concentrates X-rays onto a FPM detector at the focal plane. NICER FPM detectors are arranged in groups of eight; each group of eight feeds into a Measurement Processing Unit (MPU). There are seven total MPUs with eight parallel inputs. Each input has two signal processing chains, deemed the “slow” and “fast” channels, according to their shaping times. Thus, there are 56 built FPMs, 7 MPUs, and 112 signal processing chains.

XRC units are X-ray optics, built as 24 concentric nested shells. Each shell is composed of an aluminum foil substrate, coated with a smooth reflective gold layer. Thus, there are 56 built XRCs, and a total of 1344 individual shells.

Although FPMs, XRCs and MPUs were designed identically, and they were typically assembled from single lots of parts, there are small variations from detector to detector and from channel to channel. This document and the associated data files describes the FPM and XRC performance parameters on a module-by-module (and shell-by-shell) basis.

For the FPMs, three files are available:

- nixtipidetparamYYYYMMDDvNNN.fits - show channel resolution and low energy threshold (trigger efficiency) performance parameters
- nixtipifastdetparamYYYYMMDDvNNN.fits - fast channel resolution and low energy threshold (trigger efficiency) performance parameters
- nixtinoiseparamYYYYMMDDvNNN.fits - slow channel noise peak characterization parameters

For XRCs the following two files area available:

- nixtixrcalignparamYYYYMMDDvNNN.fits - XRC alignment parameters
- nixtixrcshellparamYYYYMMDDvNNN.fits - XRC shell throughput parameters

The following sections describe each of these files in more dtail.

Detector Performance Parameters

NICER detectors are silicon drift diode detectors (SDDs), which are packaged with their read-out, housekeeping, and thermal systems into Focal Plane Modules (FPMs). There are 56 individual FPMs, of which 52 function on-orbit.

Detector performance parameters are stored in files named like:

- `nixtipidetparamYYYYMMDDvVVV.fits` - slow chain detector parameters (PI)
- `nixtipifastdetparamYYYYMMDDvVVV.fits` - fast chain detector parameters (PI_FAST)

The NICER detector parameters collect items necessary and useful for modeling the response of each module. While modules are built to identical specifications, natural process variations lead to slight variations from module to module of their actual performances. The CALDB file collects this information into a single location.

The following columns are present in the FITS table.

NAME	Units	Description
DET_ID		Detector Identifier (10*MPU + FPM) DET_ID n9 indicates average for MPUn (DET_IDs n0-n7) DET_ID 99 indicates array average
FPM_SN		FPM fabrication serial number
FPM_BATCH		FPM fabrication batch
MPU_SN		MPU fabrication serial number
SIGMA_READ	eV	Detector electronic read noise (dark conditions)
SIGMA_READ_TREND	eV/yr	Linear trend of electronic read noise over time
FANO_EFF	fraction	Fano factor for optical photons
TRIG_ECENT	eV	Trigger efficiency function centroid polynomial coefficients w.r.t. undershoot count rate (N-vector)
TRIG_EWID	eV	Trigger efficiency function width polynomial coefficients w.r.t. undershoot count rate (N-vector)

NICER's measurement system have two separate and non-identical read-out chains. The “slow” chain has a shaping time constant of ~465 ns (nominal), and is known in event files as

PHA and PI. The “fast” chain has a signal shaping time constant of ~85 ns (nominal), and is known in event files as PHA_FAST and PI_FAST. The triggering and measurement systems for each signal processing chain is independent, which means either one, or both signal processing chain can indicate the presence of an event. Thus, there are two separate files which indicate the detector properties for each chain.

Within each file is a binary table, ordered by detector ID (DET_ID). This DET_ID identifies which detector, and is composed of the MPU number (0-6) and FPM number (0-7). It is computed as

DET_ID = 10*MPU + FPM

For example. For MPU 3, FPM 4, the detector ID is 34.

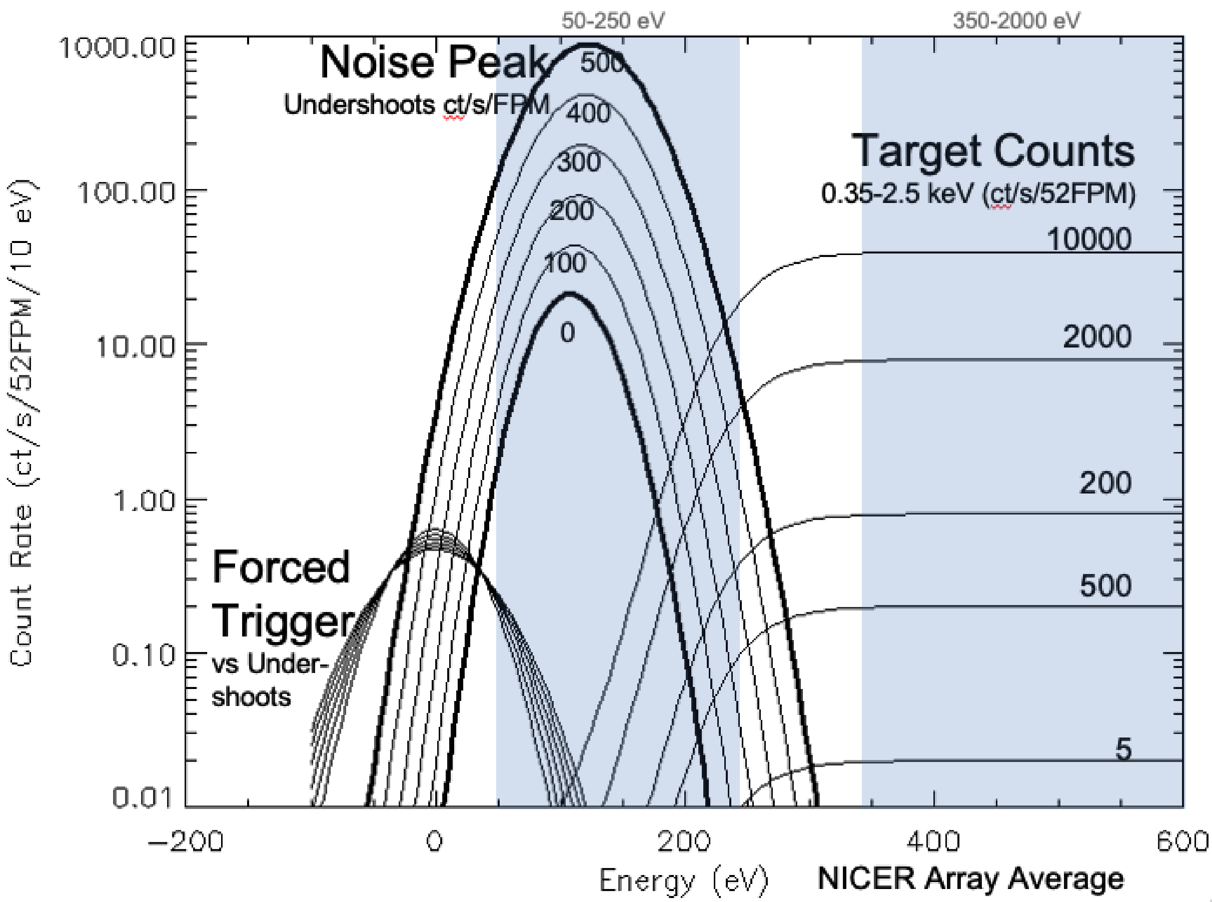

Figure 1. Representative diagram of various peaks and features in raw NICER event files. In this example, we are showing the NICER full-array rates, combining all detectors. Near 0 keV is the forced trigger peak (which may broaden with undershoots). Centered near 120-150 eV is the noise peak, which varies in amplitude, centroid and width as the undershoots vary. Near 250 eV is the centroid of the X-ray trigger efficiency curve (a flat source spectrum has been assumed). The shaded bands show the band used for the FPM_NOISE25_COUNT count rate and FPM_XRAY_PI_0035_0200 in the filter file.

Figure 1 shows a schematic of NICER detector features, including the “forced trigger,” noisse peak and trigger efficiency curves.

The file can be broken down into columns related to detector resolution and trigger efficiency. The following sections will describe those columns.

Detector Resolution Parameters

For the purposes of response modeling, the resolution of the instrument can be broken into several components.

- Electronic read noise (σ_R) amount of noise introduced into every measurement (independent of photon energy) by the electronic read-out system. This quantity is measured by using the NICER “forced trigger” data.
- X-ray fano noise (keyword SI_FANO = f_x) - energy dependent noise introduced by the inherent variation in number of converted photoelectrons. This is a number of physics for silicon, hence a single keyword covering all detectors.
- Optical fano noise (FANO_EFF = f_o) - noise introduced by optical light photons.

The resolution for a given photon can be estimated quadrature sum of all noise terms.

$$\mathrm{SIGMA} = w * \mathrm{sqrt}((R_e)^2 + R_o + R_x)$$

Where

- $R_e = \sigma_R/w$ = electronic read noise (electrons)
- $R_o = f_o * N_f * U * T_s$ = optical fano noise (electrons)
- $R_x = f_x * E / w$ = X-ray fano noise (electrons)
- σ_R = (SIGMA_READ + SIGMA_READ_TREND * t) = total electronic read-out noise with linear temporal trend (eV)
- w = SIWORKFN = energy required to create an electron-hole pair in silicon (keyword in FITS file; eV/electron)
- f_x = SI_FANO = Fano factor for X-rays in bulk silicon (fractional)
- f_o = FANO_EFF = Fano factor for optical photons in bulk silicon (fractional)
- N_f = ELECFULL = full-well capacity of detector (keyword in FITS file; electrons)
- U = undershoot count rate, per detector, taken from filter file (undershoot/sec)
- T_s = SHAPTIM = electronic shaping time (keyword in FITS file; seconds)
- E = (PI +0.5) * 10 eV = nominal photon energy (eV)
- PI = calibrated pulse height from event file (PI for slow chain; PI_FAST for fast chain)
- t = event time = (TIME - SIGEPOCH) / (1 year) = event timestamp, measured in years since the epoch
- SIGEPOCH = epoch of the detector parameter file (keyword in FITS file; MET seconds)

The slow chain electronic read noise is measured using NICER forced triggers under dark conditions. Since forced triggers are reported when no X-ray trigger is present, they represent the energy of 0 keV, which is handled by the gain calibration files elsewhere. The peak is characterized as a gaussian, whose sigma width of the peak is equivalent to SIGMA_READ. Figure 2 shows an example of the forced trigger peak for the slow channel.

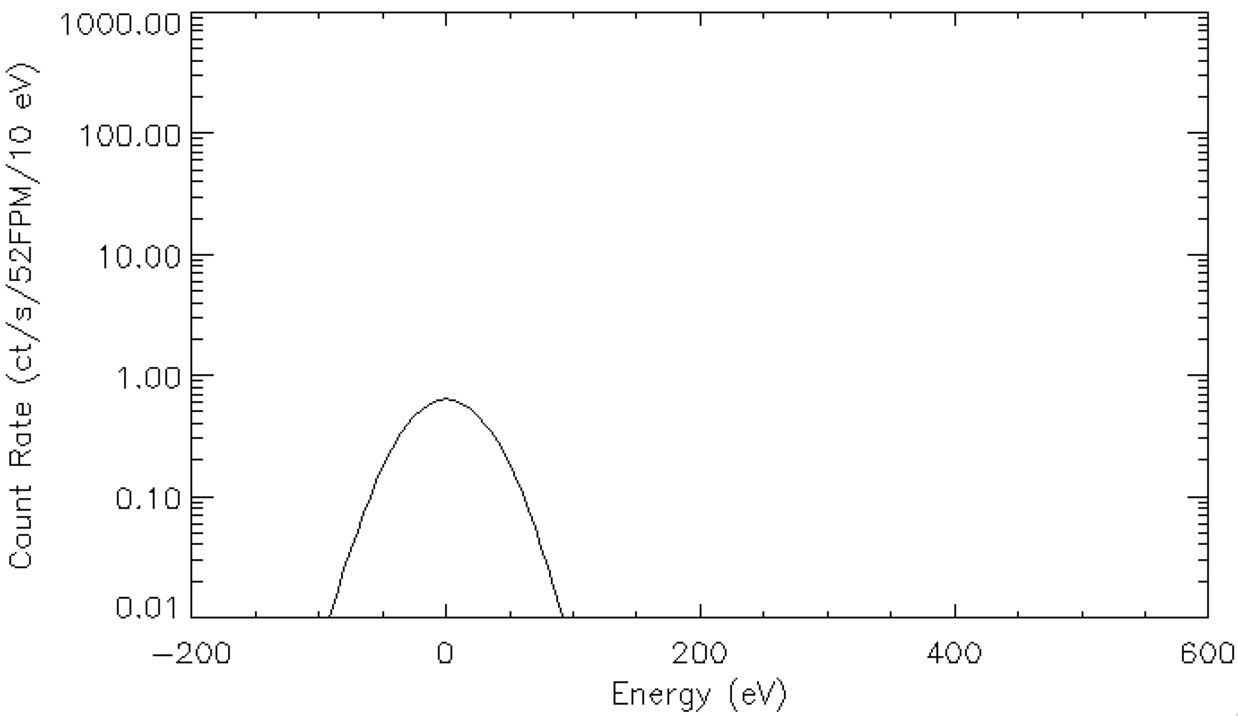

Figure 2. Forced trigger peak for a representative detector. It is centered at 0 keV, and its 1-sigma width is given as SIGMA_READ in the CALDB file.

The two Fano-like terms describe how additional stimulus injects additional noise. In the presence of optical photons, additional electron-hole pairs are injected, one for each optical photon. These create a bias or zero-point offset (which is handled during calibration), but also injects additional noise into the system.

NICER's silicon detectors accumulate charge at the read-out anode until they reach a set charge level, after which a detector reset occurs and the collected charge is discharged. This reset is also known as an undershoot count. Measuring the number of undershoots gives an estimate of the amount of optical light present, and hence the amount of noise due to optical light that is injected. An estimate of the nominal number of electrons that causes a reset, is about ELECFULL = N_f = 239,000 electrons, although this number will vary from detector to detector due to manufacturing tolerances and detector noise susceptibilities. Thus each additional reset per second represents an additional N_f electrons injected by optical light per second. However, the relevant quantity for noise calculations is the amount of noise electrons injected during the electronic shaping time period, T_s = SHAPTIME. The estimate of total electrons injected during the shaping time period is $N_f * U * T_s$, and the multiplicative factor f_o is the fano factor that describes how this number of electrons translates into actual noise.

Nominally f_o should be unity, but since the full-well capacity and shaping time are nominal values, not actual, fo also absorbs the variances into those quantities.

The energy-dependent X-ray fano factor is well documented in the literature and will not be described here.

The work function, w, is the amount of energy required to liberate an electron-hole pair in bulk silicon. This is a property of bulk silicon and the value is stored in the SIWORKFN keyword of the FITS file.

As NICER detectors age in the space environment, it is possible detect small changes in the total noise levels. We characterize that as a linear increase in the total read-out noise level as a function of time, as shown in the formula above. The epoch of the trend is given in the SIGEPOCH FITS keyword, and the trend factor is given in eV / yr.

Detector Trigger Efficiency

NICER's response to low energy photons is not simple. In fact, there is a gradual response increase from 0 to full response.   This function is known as the trigger efficiency function. In another context this might be known as the lower level discriminator level or threshold level. In reality though this is not a simple number but rather smooth transition to full response.

The reason for this transition is that due to inherent variations within the electronics, there is an energy dependent probability of surviving the low energy threshold value. Note that in addition to the trigger efficiency function, the noise peak is also normally superimposed on spectra, typically at the bottom end of the trigger efficiency curve.

Figure 3 shows the trigger efficiency function for the full-array average. The NICER team models this function based on the "error function" erf(). We used a "normalized" error function, erfn(), which is the cumulative normalized gaussian function.

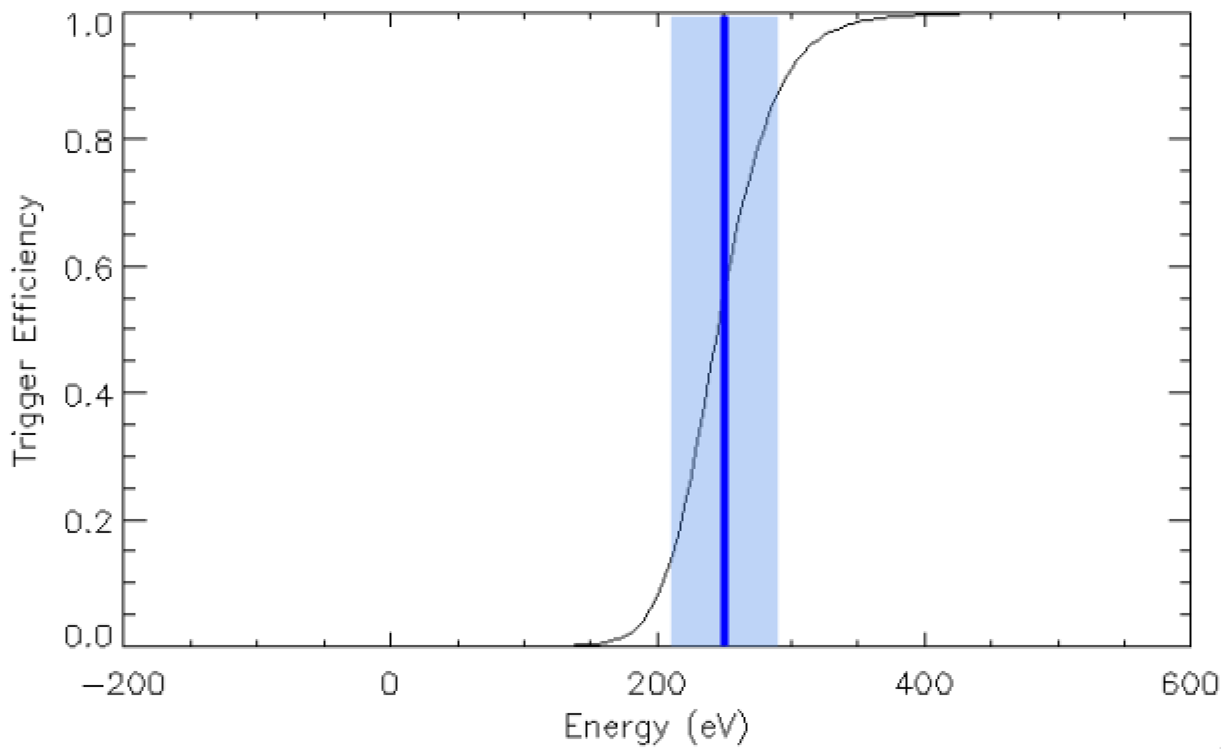

Figure 3. Trigger efficiency function for the full-array. The trigger efficiency function shape is a “normalized” erf with centroid near 250 eV and 1-sigma width of about 40 eV.

erfn(x) = 0.5 * (1 + erf(x / sqrt(2)))

As a “transmission” function, this function is a unitless function, and is normalized so that it varies from 0 to 1.0 as x passes from negative to positive. In our case, the trigger efficiency function is written as a translated and scaled version of this erf-like function.

EFF(E) = erfn((E - E_c) / E_w)

This function is characterized with the following parameters.

- Centroid value - E_c - energy at which function achieves half-max value, typically about 250 eV for the slow chain and 450 eV for the fast chain;
- Width value - E_w - 1-sigma width of equivalent gaussian, typically ~40 eV for the slow chain, and 90 eV for the fast chain;
- The maximum value is taken to be 1.0, corresponding to full quantum efficiency of the detector above threshold.

In reality, the centroid and width may be weak functions of optical loading. Therefore, these values are stored within the FITS file as an N-vector of polynomial coefficients.

E_c = POLY(U, TRIG_ECENT)
E_w = POLY(U, TRIG_EWID)
POLY(x,P) = SUM(P[n+1] * x^n) starting from n=0

The last function is a Taylor-series polynomial expansion of each of these variables about U, undershoot rate, starting with the 0th term. The number of vector elements in the FITS file for TRIG_ECENT and TRIG_EWID determine the number of polynomial terms to include. Since FITS does not have a 0th element, TRIG_ECENT[1] is the 0th order term, TRIG_ECENT[2] is the 1st order term, and so on.

More specifically,

- TRIG_ECENT - n-vector in FITS file to evaluate trigger efficiency centroid
  TRIG_ECENT[1] = centroid at dark conditions (undershoots = 0) (eV)
  TRIG_ECENT[2] = linear trend of centroid versus undershoots, (eV/ushoot)
  TRIG_ECENT[n] = additional polynomial terms (eV/ushoot^n)
- TRIG_EWID - n-vector in FITS file to evaluate trigger efficiency width (eV)
  Similar polynomial layout
- U = undershoot count rate for each FPM (undershoot count / second)
- E = (PI +0.5) * 10 eV = nominal photon energy (eV)
- PI = calibrated pulse height from event file (PI for slow chain; PI_FAST for fast chain)

This function is evaluated by the NICER response calculator.

Development and Revision History of Resolution & Trigger Efficiency Parameters

The detector resolution parameters were measured on-orbit by sampling the forced trigger data. A mission-long database of forced trigger measurements were accmulated, as a function of undershoot rate, and the peak centroid, width and amplitude were estimated in six month chunks. The values in the “v001” file were derived using the “optmv12” gain solution.

The detector trigger efficiency centroid values were measured on-orbit using astrophysical observations of bright, highly absorbed targets (LMC X-3 and SWIFT J0243). These targets are ideal for such a study because the absorption is strong enough that only the incomplete charge collection shelf is apparent at low energies, and that shelf is a useful flat continuum against which to measure the trigger efficiency function. The values were estimated by the MIT instrument team using the “optmv10” gain solution.

The trigger efficiency versus undershoot sensitivity coefficient was derived from special observations of the Crab nebula, and processed by the MIT instrument team. The low energy threshold was raised to place it at about 1 keV, where the density of Crab counts per eV is the highest. Observations were taken near the orbit day-night boundary in order to get good measurements of the trigger efficiency function at low and high undershoots.

Detector Noise Parameters

NICER detectors exhibit a distinct noise peak. This noise peak is composed of electronic noise triggers that fall slightly above the lower level discriminator threshold, and therefore trigger event processing.

Theoretically, the origin of the peak is the fraction of noise signal that exceeds the discriminator threshold.

Phenomenologically, the peak appears as a gaussian-like peak centered near 120 eV and with a 1-sigma width of about 25 eV. However, the location, amplitude and width of the peak varies from detector to detector and also varies with optical loading (undershoot rate). The amplitude varies approximately exponentially with undershoot rate. This can be understood because the electronic read noise increases with optical loading due to injection of optical photoelectrons. As the noise signal becomes broader, more of the peak exceeds the discriminator threshold, and hence more noise events are expected. The amount of gaussian tail probability scales approximately exponentially with tail cut, hence the exponential dependence.

Figure 4 shows the approximate noise peak behavior with energy and undershoot rate.

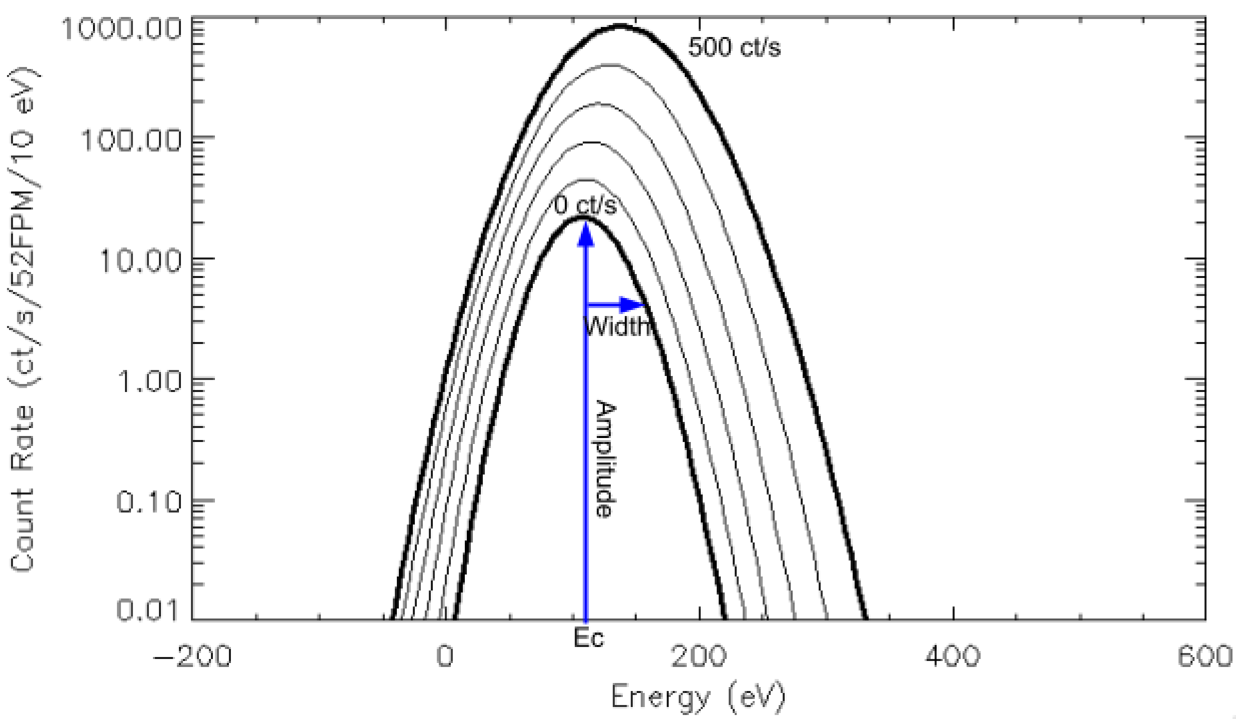

Figure 4. NICER array-summed noise peak, versus energy and versus undershoot count rate. The curves are for per-detector undershoot count rate of 0 (bottom) to 500 ct/s (top) in steps of 100 ct/s. Note that the amplitude, centroid, and width all change as undershoot count rate

varies. The gaussian peak is characterized in terms of amplitude, 1-sigma width, and centroid (Ec).

The following columns are present in the FITS table.

NAME	Units	Description
DET_ID		Detector Identifier (10*MPU + FPM) DET_ID n9 indicates sum for MPUn (DET_IDs n0-n7) DET_ID 99 indicates array sum
NOISE_RATE	ct/s	Noise peak rate in dark conditions
NOISE_TREND	ct/s/yr	Noise peak rate annual linear trend
NOISE_EFOLD	electron	Noise peak-undershoot folding scale (polynomial N-vector)
NOISE_ECENT	eV	Noise peak centroid energy (polynomial N-vector)
NOISE_SIGMA	eV	Noise peak 1-sigma width (polynomial N-vector)
NOISE_FANO_EFF		Noise peak optical Fano factor

While NICER has two signal measurement chains, a slow and fast chain, the noise peak effectively only shows up in the slow (PI) measurement chain. Therefore there is only one noise peak parameter file, for only the slow channel.

Please note that, even after gain correction, the noise peak is not at a fixed energy. This is because the detector noise is not a fixed-energy process, but rather a random process that broadens (accesses higher apparent energies) with more optical loading. Therefore, the properties of the peak are characterized as a non-linear function of undershoots.

As mentioned above, the noise peak appears as a gaussian. We model the noise peak counts as follows,

$$dN = A_N\ G(E, E_C, \sigma_N)\ dE$$

where $G(E,E_C,\sigma_N)$ is a normalized gaussian function with centroid E_C and 1-sigma width of σ_N:

$$G(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}\right)$$

The noise function dN here is scaled to produce the number of counts per second in a 10 eV PI bin, i.e. dE = 10 eV. The amplitude A_N is the noise peak amplitude, which itself is a function of undershoots and time.

E is defined to be the nominal photon energy (see below).

The amplitude terms in the formula above can be calculated as follows:

- A_N dE = A_0(t) * A_U(U) dE - this is the total noise rate, which has a time dependent term (t) and undershoot term (U) (ct/s in each 10 eV bin)
- A_0(t) dE = (NOISE_RATE + NOISE_TREND*t) - this is the noise rate in dark conditions, which has a post-launch and time-dependent term (ct/s in 10 eV bin); the 10 eV bin size is implicit in the NOISE_RATE and NOISE_TREND columns in the FITS file;
- A_U(U) = exp(U*N_f/N_e) - is the undershoot-dependent factor, which is exponentially dependent upon the undershoot rate (but otherwise unitless)
- N_e = POLY(U, NOISE_EFOLD) - noise folding scale, in electrons, which has a weak polynomial dependence upon the undershoot rate, U
  POLY(x,P) = SUM(P[n+1] * x^n) starting from n=0
- See below for the definitions of some variables such as t, E and U

The centroid of the gaussian, E_C, is calculated as

E_C = POLY(E, NOISE_ECENT)
POLY(x,P) = SUM(P[n+1] * x^n) starting from n=0

where NOISE_ECENT is an n-vector stored in the FITS file.

The total 1-sigma width of the gaussian, σ_N, can be decomposed into components due to the intrinsic width and a Fano-like component due to optical loading

$$\sigma_N^2 = \left(\sigma_{0N}^2 + \sigma_{fN}^2\right)$$

where

- σ_{0N} = NOISE_SIGMA - the noise 1-sigma width in dark conditions (eV)
- σ_{fN} = w * f_o * N_f * U * T_s - the optical fano term (eV)
- w = SIWORKFN = energy required to create an electron-hole pair in silicon (keyword in FITS file; eV/electron)
- N_f = ELECFULL = full-well capacity of detector (keyword in FITS file; electrons)
- U = undershoot count rate, per detector, taken from filter file (undershoot/sec)
- T_s = SHAPTIM = electronic shaping time (keyword in FITS file; seconds)
- f_o = NOISE_FANO_EFF = Fano factor for optical photons for the noise peak (fractional)

Energy and time are defined as follows in this section:

- E = (PI +0.5) * 10 eV = nominal photon energy (eV)
- PI = calibrated pulse height from event file (PI for slow chain; PI_FAST for fast chain)

- t = event time = (TIME - NOIEPOCH) / (1 year) = event timestamp, measured in years since the epoch
- NOIEPOCH = epoch of the detector noise parameter file (keyword in FITS file; MET seconds)

Development and Revision History of Noise Peak Parameters

The detector noise peak parameters were measured on-orbit by sampling all data throughout the NICER mission to date (approximately January 2021). A mission-long database of all observations was accumulated, and filtered to remove outliers and bright astrophysical targets that might interfere with the noise peak. Forced trigger events were excluded as well. The noise peak parameters were measured as a function of undershoot rate, and the peak centroid, width and amplitude were estimated in six month chunks. The values in the "v001" file were derived using the "optmv12" gain solution.

XRC Alignment and Throughput Parameters

NICER is composed of 56 individual co-aligned telescopes. Here "co-aligned" is a true statement, subject to possible variances in the pre-launch assembly and test process, as well as any post-launch shifts (perhaps due to launch loads or due to gravity loading release)

Each telescope is composed of a unique FPM, which has been described above, and a unique X-ray Concentrator (XRC) module, and each pair is uniquely aligned. Each of these modules was individually built and integrated. Overall, each module contributes to a total co-aligned instrument. However, at the next order, there are small misalignments of modules which can affect performance. These quantities are documented in the `nixrcalignparamYYYYMMDDvVVV.fits` and `nixrcshellparamYYYYMMDDvVVV.fits` files.

The following columns are present in the "align" FITS table.

NAME	Units	Description
DET_ID		Detector Identifier (10*MPU + FPM)
Q_MISALIGN		Misalignment quaternion [4-vector]
Q_TIP		Quaternion which transforms from payload coordinate system and XRC optic "tip" coordinate system
TIP_ANGLE	arcsec	XRC optic tip angle around payload "-Y" direction
TIP_AZIMUTH	deg	Azimuth angle of XRC optic tip angle plane with respect to payload coordinate system

For NICER, alignment is considered to be composed of two aspects

- The boresight alignment of an XRC + FPM telescope pair. The boresight is defined as a straight line that passes through the centers of the XRC and FPM. Note that the boresight axis is independent of the optical axis of the XRC optic, although they were designed and built to be co-aligned.
- A misalignment of the XRC optical axis, considered to be a “tip” in a certain direction. The NICER team models the tip as a rotation of the optic by a certain angle, the “tip angle,” within a given rotation plane. The azimuth of the rotation plane is given by the “tip azimuth.”

The Q_MISALIGN quantity is a quaternion [4-vector] which represents the misalignment of the boresight a given module with respect to the NICER payload coordinate system. Unlike the mission-level `nixtipntmis20170601v001.teldef` TELDEF file, which provides overall payload-level pointing alignment information, the Q_MISALIGN provides boresight misalignment for each module separately. Note that the NICER team does not maintain alignment knowledge of each individual shell.

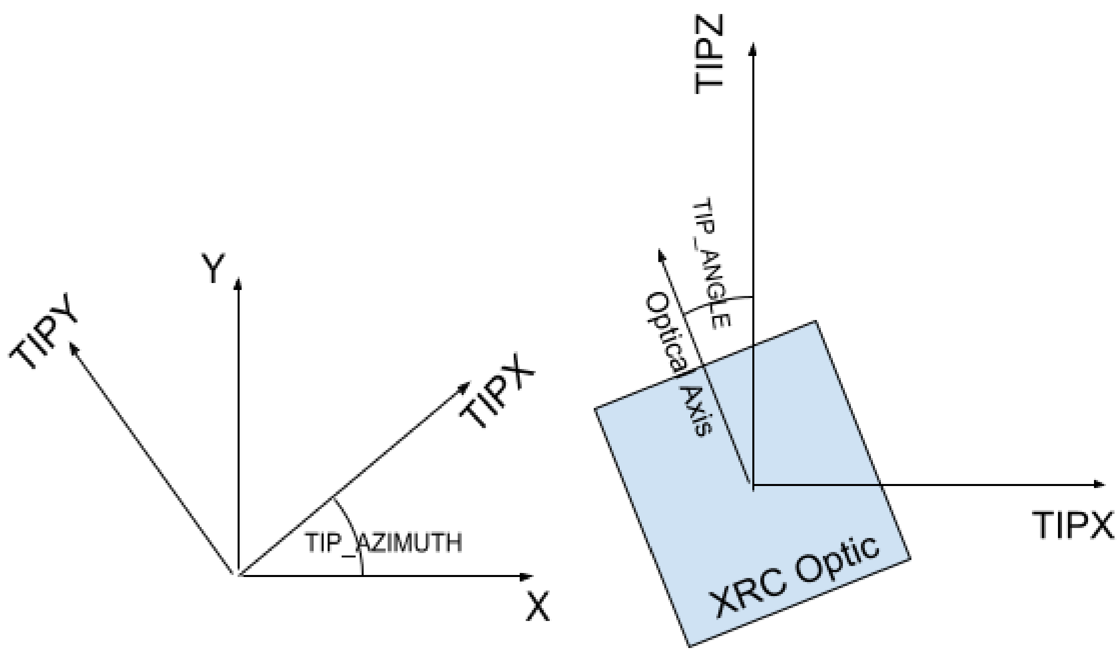

Figure 5. Definition of “tip” coordinate system. (left) The TIP_AZIMUTH angle is the rotation of the tip coordinate system about the shared Z axis, relative to the NICER payload coordinates. (right) The TIP_ANGLE is the rotation of the XRC optic’s optical axis in the TIPX-TIPZ plane.

The TIP_ANGLE and TIP_AZIMUTH quantities represents the magnitude and direction, respectively, of any tip of the XRC optical axis (see Figure 5). The TIP_AZIMUTH specifies the tip rotation plane, and is an azimuth angle measured about the payload +Z coordinate axis. The TIP_ANGLE specifies the amount of tip, usually between 0 and 90 arcseconds.

The Q_TIP quantity is a quaternion which represents the transformation between NICER payload coordinates and the optic "tip" coordinates. Since all vignetting profiles are specified in teh tip coordinate system, this is useful for calculating vignetting data. The "tip" coordinate system +Z axis is co-aligned with the boresight axis, and the tip plane is aligned with the +X axis. Thus, the following transformation is true,

Q_TIP = Q_MISALIGN * Q(+Z,+TIP_AZIMUTH)

where "*" is quaternion multiplication and Q(u,θ) is a quaternion consisting of a rotation by angle θ about the unit vector u.

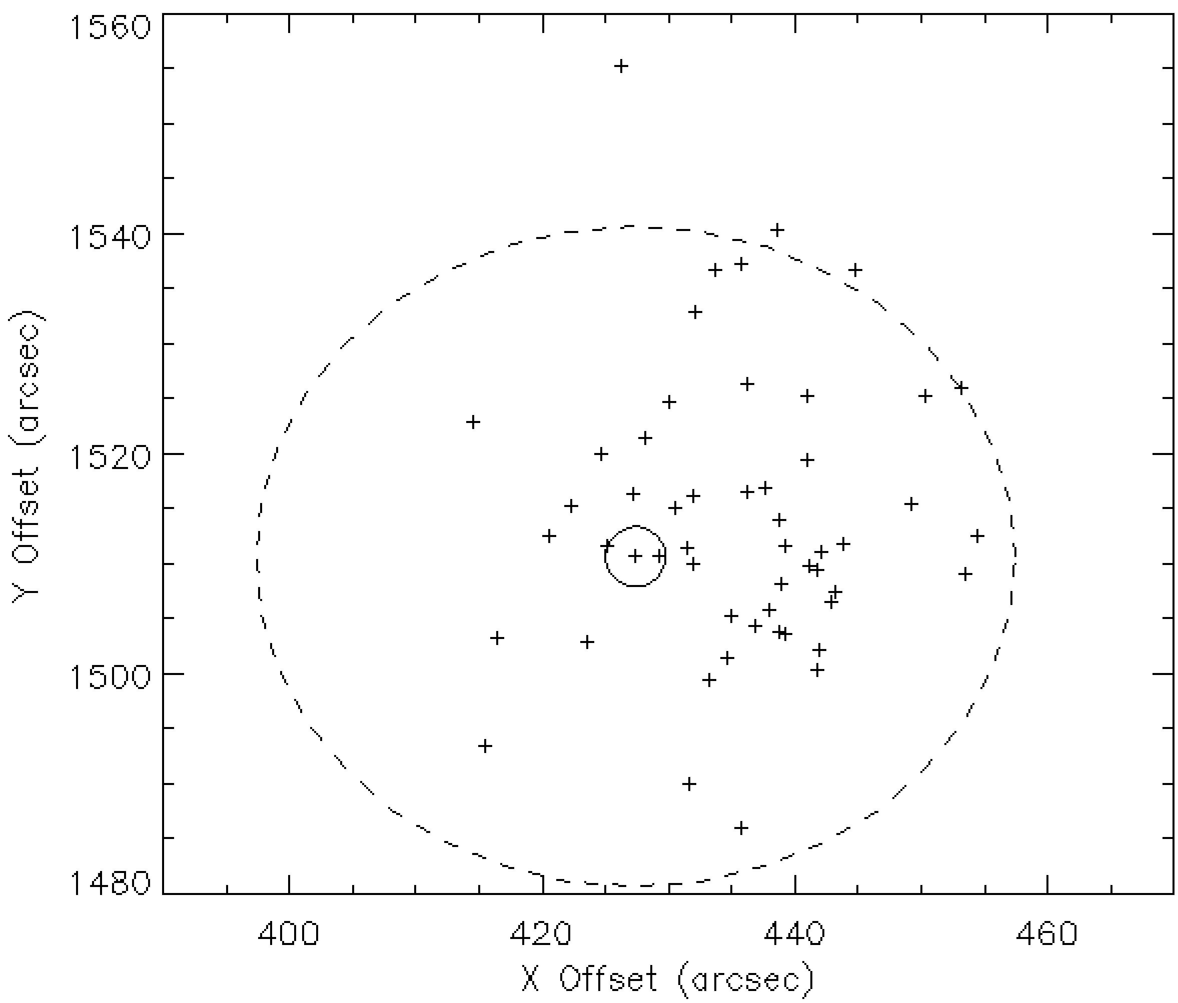

Figure 6. Estimated boresight of each NICER module (+ symbols). The coordinate system is the NICER star tracker coordinate system. The overall NICER boresight for pointed observations is also displayed (small circle), and a circle of radius 30" (dashed) is also shown, which has the approximate response of 97% of maximum.

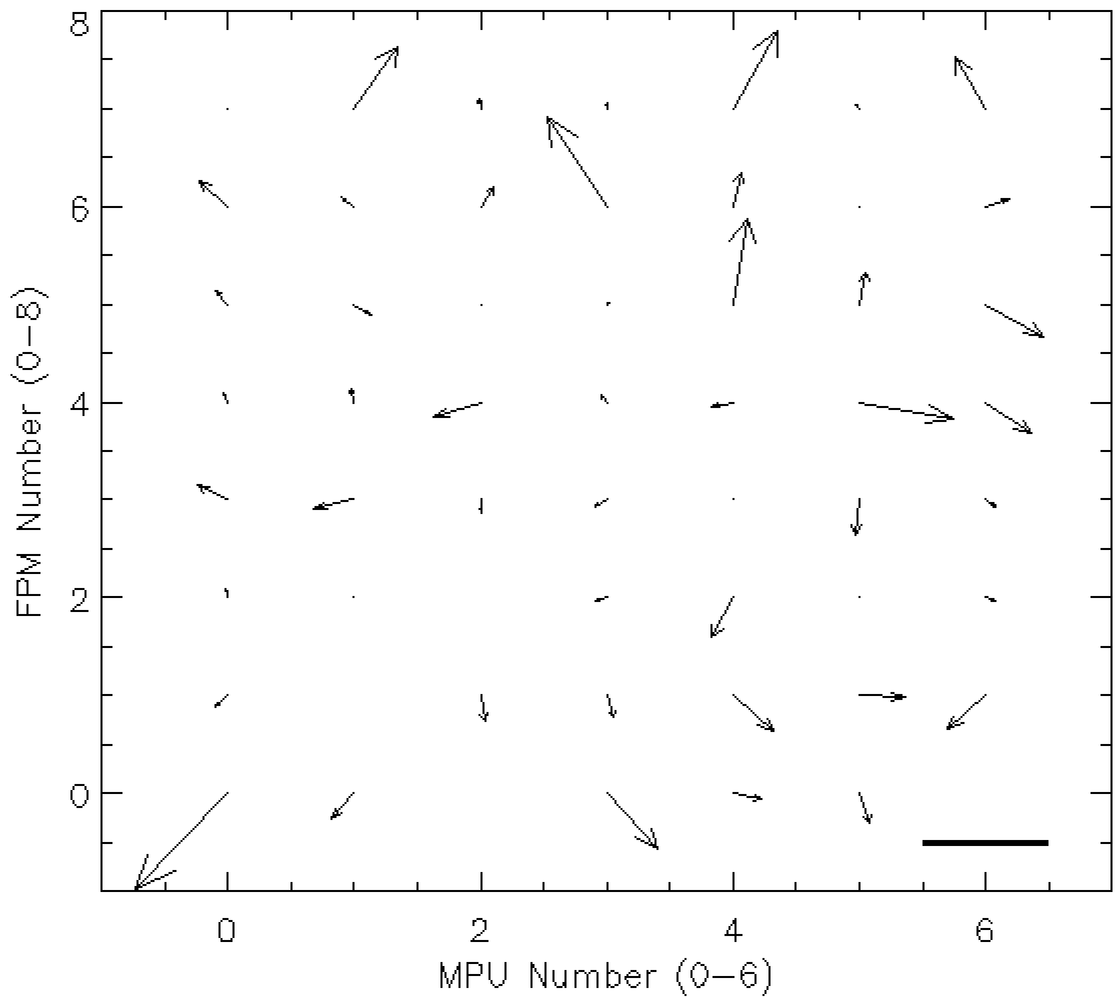

Figure 7. Estimated tip angle and azimuth for each module. Each module is shown originating from it's coordinate location (example: DET_ID 40 originates from position (4.0,0.0)). The direction of the vector is the azimuth angle of the tip, and the magnitude is the tip angle. For reference a bar of 75 arcsec is shown in bold in the lower right corner.

Figures 6 and 7 show the estimated boresight and tip parameters for all NICER modules. Concerning the boresight, it is clear that almost all modules are aligned to within a few tens of arcseconds. The standard deviation is 16 arcsec. Concerning optic tip parameters, most optics are aligned to better than 10 arcseconds. However, a handful of optics are tipped between 40 and 75 arcseconds. The response of these optics can be handled by considering the general vignetting profile as a function of tip angle using ray-tracing. This is the subject of a different document.

The following columns are present in the “shell” FITS table.

NAME	Units	Description
DET_ID		Detector Identifier (10*MPU + FPM)
SHELL_ID		Shell identifier (1=innermost; 24=outermost) SHELL_ID=99 indicates module average
AU_SURFACE_RMS	um	XRC surface gold micro-roughness
NORM		Throughput normalization for shell/module (unitless)

Each NICER XRC is composed of 24 nested foil shells. The shell substrate is formed aluminum foil, and the surface coating is gold replicated from a surface mandrel. This file provides information about each shell, or in some cases information about the module-level assembly (all 24-shells integrated and aligned). These values are used to calculate an accurate effective area or “ARF” for a given observation based upon given observation conditions.

The overall effective area of each XRC is governed by the optical throughput. This in turn is controlled by the form of each optic, as well as the surface gold properties such as density and surface micro-roughness. We have performed detailed ray-trace simulations of the optical throughput capabilities of NICER’s XRCs in the ideal, for a variety of surface roughness values. These were compared to calibration observations of the Crab Nebula with a template spectrum. Variations from detector to detector were attributed to either surface roughness and/or an arbitrary throughput factor between 0 and 1.0. Thus, each shell is assigned a roughness value as well as a throughput normalization, which is used for estimating the effective area or ARF.

Development and Revision History of XRC Alignment and Throughput Parameters

NICER’s shell-by-shell throughput calibration was estimated using on-axis observations of a well-known bright calibration target, the Crab Nebula. As described in the release notes for CALDB release xti20200722, a detailed spectral template model for the Crab pulsar + nebula was developed and applied to NICER observations. Individual shell throughput parameters were adjusted in order to match the template model.

For throughput calibration file “v001”, the throughput values were estimated following the methodology of the xti20200722 CALDB release. The following values were allowed:

- Surface roughness any value between 2.5A and 12 um
- Throughput any allowed value (0-1)

- Analysis “prior” so that poorly constrained values are loosely constrained to be near array-average mean

For throughput calibration file “v002”, the NICER team has simplified the approach somewhat with minimal loss in performance. These parameters were used internally and not recommended for any public analysis.

- Surface roughness of 8A (shells 1-2)
  Surface roughness of 4.5A (shells 3-24)
- Throughput any allowed value (typically 0.8-1.0)

For throughput calibration file “v003”, the NICER team used the same approach as “v002,” but used the “v003” alignment file as input.

These constraints still allow good fits to the Crab nebula with more physical values of the roughness and throughput normalization. They also allow a more simplified process for computing the effective area for a given observation, since the selection of roughness values is considerably reduced.

For alignment calibration file, raster observations of the Crab nebula from early mission days were used to estimate the tip of each optic as well as its misalignment from the observatory boresight.

For alignment calibration file “v001”, a simple gaussian vignetting profile was used to fit the Crab raster pattern. No optical tip was assumed. (i.e. “v001” all tip angles are set to 0).

For alignment calibration file “v002”, a more detailed vignetting profile based upon ray-trace simulations. Individual tip angles, azimuths and alignments were estimated on a per-module basis. This file was used internally and not recommended for public usage.

For alignment calibration file “v003”, the approach of “v002” was used with additional filters to remove times of high pointing jitter (maximum jitter of 60 arcsec), and also to apply an optimal amount of smoothing that produced the minimum-variance solution (i.e. lowest combined boresight offset + tip angle offset).