NICER CALIBRATION: Improvements to NICER Energy Scale (optmv7 & optmv7he)

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Introduction

This document briefly describes improvements to the NICER energy scale. These improvements build upon the “grand” recalibration effort in 2018. A summary of changes is below.

Release Date	NICER CALDB Ver	Internal Name	Energy Range Changed	Comments
2018-02-26	xti20180226	optmv7	Full Range	Energy scale known to ~5 eV over 0.25 keV - 8 keV range
2019-05-16	xti20190516	optmv7e	> 10 keV	Typical change of 10s of eV (300 eV max)
2020-02-02	xti20200202	optmv7he	> 8 keV	Typical changes of 100s of eV (1500 eV max near 15 keV)

As can be seen from the table above, the primary focus of optmv7 and optmv7he are the energy range above 10 keV.

optmv7e Energy Scale Model Development

The NICER optmv7e model (released publicly May 2019 as gain file nixtiflightpi20170601v002.fits) contains improvements to the NICER energy scale primarily above 12 keV. Calibration work revealed that the pulse height to charge conversion table had irregularities above a certain energy, typically above 12 keV. These irregularities could manifest themselves as certain pathological conditions, such as non-monotonic energy scale (i.e. energy scale “going backwards” as well as discontinuous jumps. These effects were the result of edge effects introduced during the 2018 grand calibration effort. Here “edge effects” means the effect of interpolation interference at the upper boundary of the table around 15-18 keV. The solution was to perform a smooth fit to the data below the discontinuities and extend that fit to higher energies.

Figure 1 shows an example of the approximate energy to channel relation for DET_ID 50. After correction, the artifact above PHA 3900 is removed.

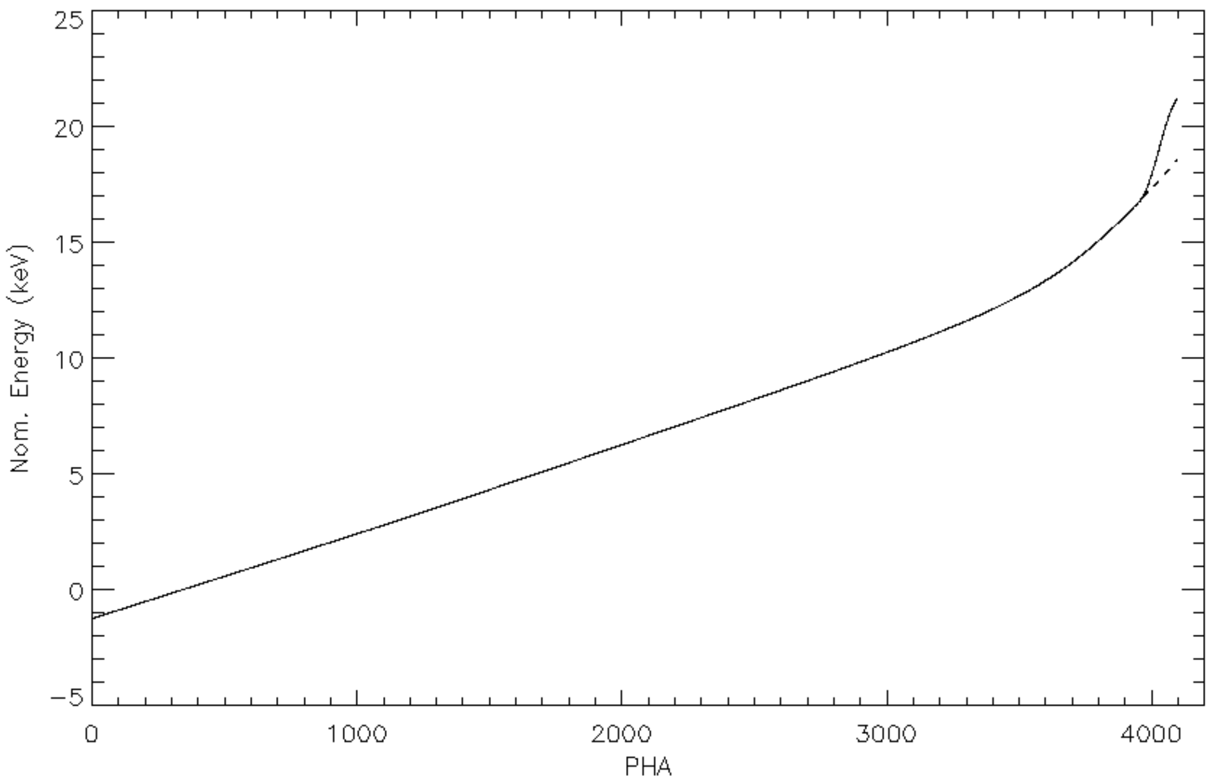

Figure 1. Approximate energy to channel relation for NICER DET_ID 50. The optmv7 (old) solution is solid; the optmv7e (new) solution is dashed.

Figure 2 shows the difference between the optmv7 baseline and the optmv7e improvement for all NICER modules stacked together.

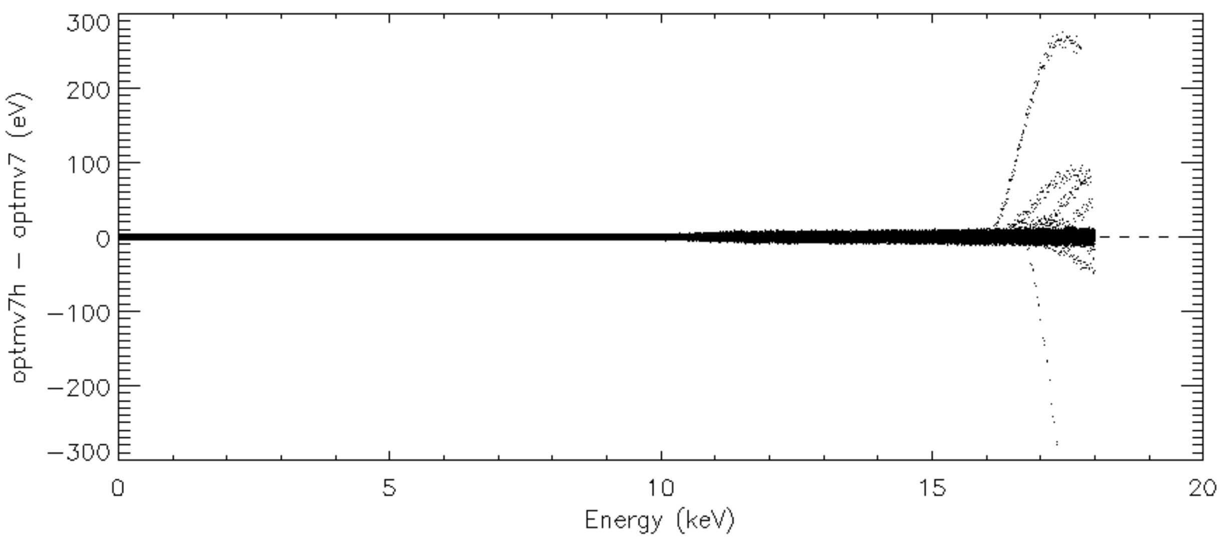

Figure 2. Difference between optmv7e and optmv7 over the entire NICER energy range.

The plot shows that almost all of the change is above 15 keV, although there are small changes at the 10-20 eV level in the 10-15 keV range. There is no change below 10 keV.

optmv7he Energy Scale Model Development

A new energy scale has been developed, dubbed optmv7he, which further improves the energy scale at the high energy range above 10 keV.

During the grand calibration work, we made several assumptions about how the energy scale would behave at low energies and extrapolated this trend to high energies.

The NICER slow channel energy scale contains a “kink,” typically at about 10 keV, where the energy to channel relation changes slope. The fast channel does not have any kink, or at least it is much reduced. In Figure 1 above the change in slope is gradual and occurs at about PHA 3500, but each detector is unique. In some detectors the “kink” is sharper. During the grand reprocessing, we had little information about how the “kink” would behave after the post-launch shifts.

For optmv7he, we used the fast channel as a reference baseline. We used a dataset composed of all background fields, which contains both high and low background levels, but importantly it contains background events that span the full NICER energy range. In some sense this is a “flat field” that fills the energy range with a nearly uniform set of events. Figure 3 shows an example of this trend as a density histogram.

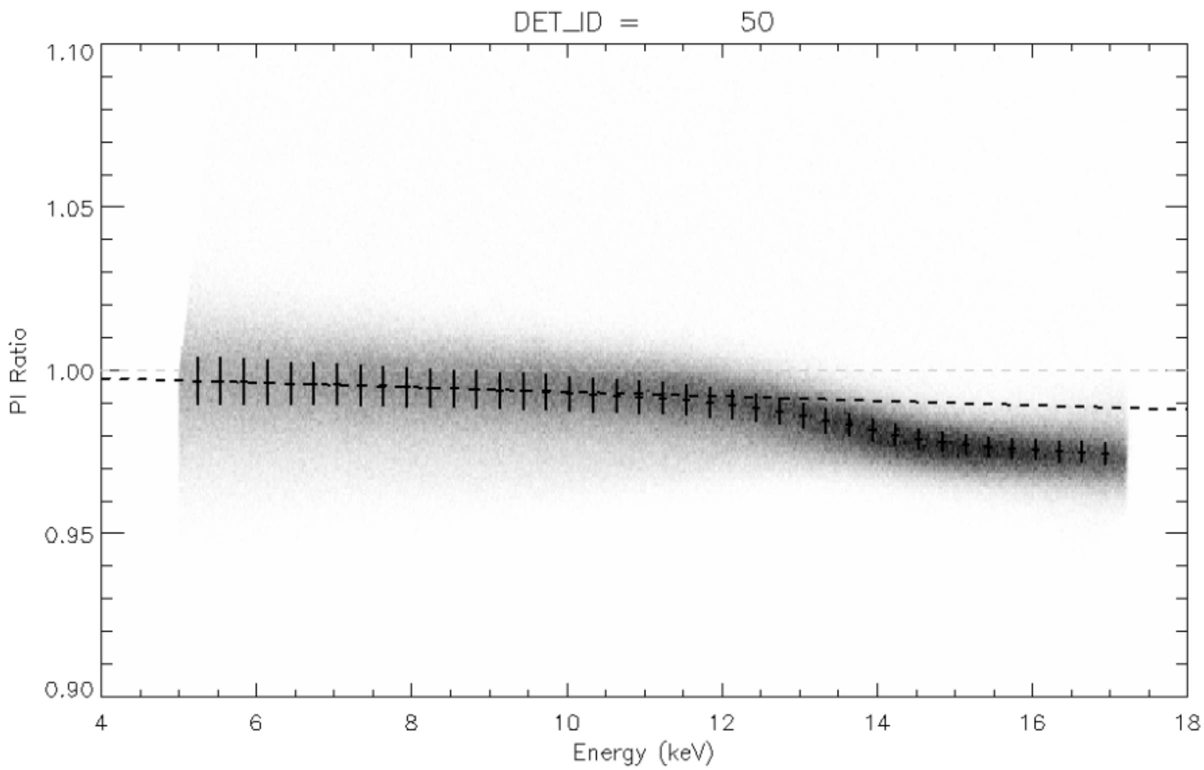

Figure 3. 2d density histogram of PI_RATIO (vertical) and energy (horizontal; slow channel energy) for NICER background events in DET_ID 50. The “expected” unity line is show in light gray dashed line. Also shown are the centroids of the density histogram slices in 300 eV steps (crosses); and the linear fit to the crosses in the 5.5-8 keV band (dashed line).

We measured the PI ratio (PI / PI_FAST) of all those events at each energy slice (in the narrow ratio range of 0.9-1.1). Here the slices were 300 eV. Nominally all events should lie on the flat ratio of 1.0. Any deviations can reflect an error in the energy scale of the slow or fast channels.

Assumptions made:

- The fast channel does not have significant sharp variations of energy to channel, so any such variations seen are errors in the slow channel
(fast channel errors are at worst linear with energy)
- Any biases introduced by using a non-imaged background are neglibible
(the centroid of the background represents the centroid of an imaged source)

We do allow for errors in the fast channel. We fit the ratio offsets in the 5.5-8.0 keV range with a linear trend. In this energy range the slow channel error should be effectively zero because we had effective energy calibration lines to measure in the slow channel. Thus, any error in that range can be attributed to a fast channel error. We extrapolate that trend to higher energies. Any deviation of the ratio from this trend line above 8 keV, we attribute as a slow channel error.

The question of biases introduced by a non-imaged background are interesting to consider. In principle, a non-imaged source of counts such as background, which interacts at all detector positions, will have a different PI_RATIO than an imaged source, which interacts at the center. This is because the electron charge cloud spreads out due to diffusion as it travels inward to the collection point. Charge clouds from interactions farther from the detector center travel farther, and thus diffuse more, which can change the rise time. This is known as the “ballistic deficit” problem.

However, in practice the mean ballistic deficit is small, typically 10s of eV, and is likely to be negligible. Furthermore, it varies approximately linearly with energy. Since we fit out a linear error trend, most of non-imaged biases will be removed. Finally, above 8 keV, we simply do not have many well established references that can be used for calibration purposes. This technique is the best we can do. Unlike the performance below ~8 keV, where we typically promise ~5 eV energy scale errors, above 8 keV, we will likely have to admit higher errors, typically ~50 eV.

The final corrected slow channel energy is computed as:

NEW_SLOW = OLD_SLOW x (Extrapolated trend) / (PI_RATIO centroid)

where “Extrapolated trend” is the linear trend extrapolated to all energies; and “PI_RATIO offset” is the centroid measured in the plot above. The adjustment was only done above 8 keV; below 8 keV no change was made. This new correction (“optmv7he”) was captured for each module and embedded in a new pulse height conversion table.

Figure 4 shows the performance of optmv7he compared to the baseline of optmv7, as a function of energy.

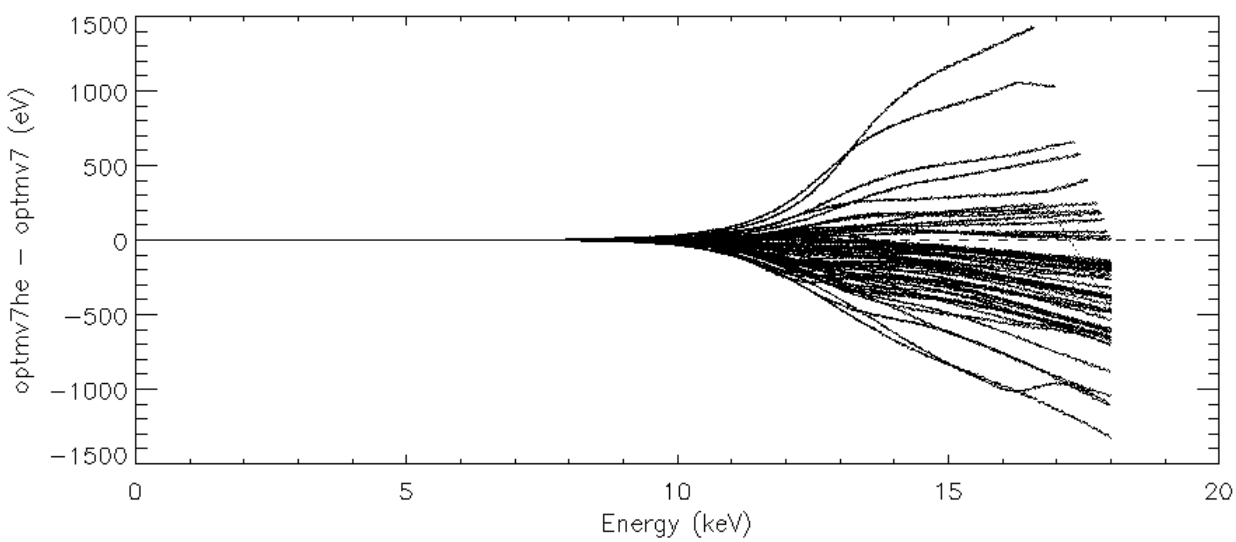

Figure 4. Difference between optmv7he and optmv7 over the entire NICER energy range.

This figure has a different vertical scale than Figure 2 because the adjustments are much larger. The mean change above 8 keV is -62 eV while the standard deviation is 220 eV. Above 12 keV the changes are much larger: mean change of -138 eV and a standard deviation of 328 eV. The maximum change is about 1500 eV.

Note that in the figure above the top traces stop before they reach 18 keV. This is because for these detectors the maximum pulse height of 4096 occurs below 18 keV.

Performance: SAA Lines

Caveats

For the general user there are a few caveats to bear in mind when using the new NICER energy scales.

It is recommended to use ‘nicerl2’ to completely reprocess your data from scratch.

However, it is possible to run ‘nicerpi’ with recal=YES, and recalibrate an existing cleaned and screened event file. There is a “gotcha” with this technique however. When you do this, the original unscreened event file is not available: the event energies are adjusted in place. **The gotcha occurs at the edges of the energy boundary used for selection.** Say for example photons with event energies 0.5 - 3.0 keV were selected. After recalibration, some photons will be moved upward or downward. A sample photon at 2.99 keV might be moved to 3.01 keV, out of the energy range of interest but it is still listed in the event file.

Even worse, if the user had worked with the unscreened event file, there would also be photons at 3.01 keV in the original unscreened event file that would potentially have moved down to 2.99 keV, but if you work with only the screened event list, this photon is not available to move down, and this creates an artificial deficit just below the upper energy buondary. Thus, there will be subtle edge effects around the boundaries of energy selection. As long as the user selects a wider energy range than the true range of interest, and then only downselects when performing the final analysis, recal=YES is a useful option. The amount of extra margin should be comparable to the change in gain solution noted above.

Also, for purposes of comparison, you may wish to run an old versus new comparison. please be aware that nicerpi uses a randomizer at the sub-PHA level. This will lead to **off-by-one differences between the old and new event lists** which are entirely expected.