NICER CALIBRATION: Release Notes of xti20200722 (optmv11, consim135p, RMF 6s)

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Version 1.0 2020-07-22
Version 1.1 2020-08-13 - Fix energy scale file names
Version 1.2 2020-08-25 - Fix RMF name to be v002.rmf (~~v001.rmf~~)

Introduction

This document describes developments and performance of NICER Calibration release xti20200722. This release contains improvements of:

- Energy scale solution “optmv11”
- Significantly revised effective area (ARF) titled “consim135p”
- Response matrix (RMF) version 6s

Summary

This page documents NICER calibration products released to the NICER team, known internally as the "March 17" release. This is released to the public as CALDB xti20200722. Summary of results:

- Crab residuals <2% in range 0.24 - 14 keV
- Joint revisions to energy scale (optmv10/optmv11), RMF (6s), ARF (CONSIM135p) are all linked
- Energy spacing of new products changed to match ISM fine structure present in tbabs model
- Higher fidelity Crab model that includes curvature of nebula, pulsar, dust scattering halo

Example residuals are shown in Figure 1.

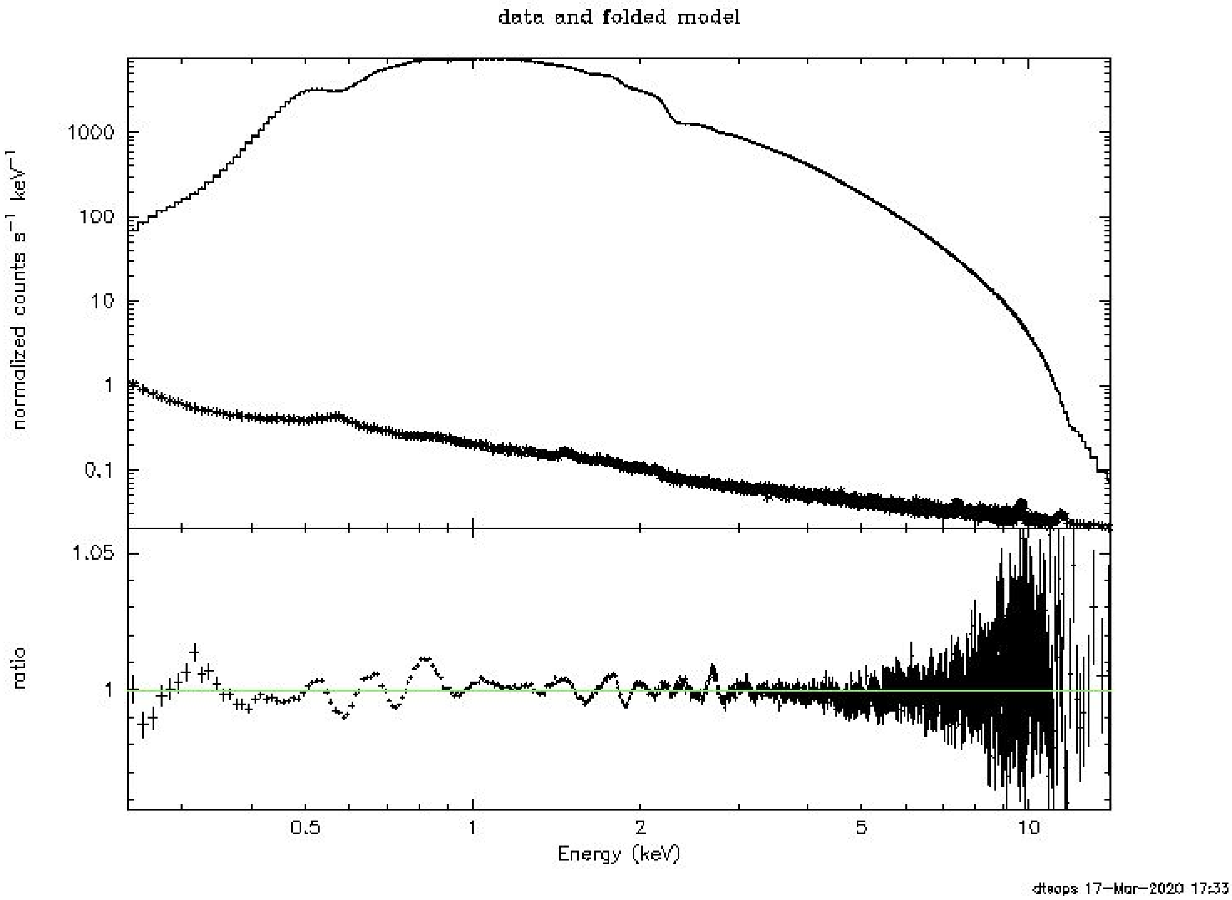

Figure 1. Example residuals after fitting the Crab Nebula using NICER calibration release xti20200722.

There are small systematic residuals across the board (<2%), but otherwise the fit is excellent.

Domain of Applicability

The current fits to the Crab are in the energy range 0.24 - 14.0 keV. We expect that most spectral fits can be performed in that energy range with good success.

Systematic errors. Relative systematic errors can be expected to be less than 1% in the 0.4 - 10 keV range. Below 0.4 keV there are several uncertainties that start to compete (gain scale, RMF parameters, intrinsic Crab spectrum including Carbon edge profile) so errors may be as large as 5-10% in that range. Above 10 keV, expect systematic errors to be 10%. For bright sources we recommend to set 1% systematic errors using the XSPEC "systematic 0.01" command. Although this does not quite capture the energy-dependent systematics, it will be a good rule of thumb for most observations.

Absolute flux scale. The absolute NICER flux level is not pegged to another observatory or flux reference point. However in the process of fitting the Crab data, there is no doubt that NuSTAR's "absolute" flux calibration (Madsen et al. 2017) has guided the calibrator's hand. Note that in the work here, the Crab spectra have been corrected for instrumental deadtime using the filter file's mean deadtime measurements. For the Crab, the deadtime correction factor is about 8%.

Flux dependence. We are not aware of any flux dependence on the response matrix. Above ~2 Crab pile-up becomes significant and will distort the spectrum in a complicated and non-linear fashion. At much fainter fluxes, background will be the dominant systematic flux error rather than the response components.

Optical loading dependence. All of the results here are based on filtering to get low optical loading (near-dark conditions). We selected array undershoots less than 50 ct/s for all Crab data (underonly_range=0-50). Unfortunately, many NICER data sets were taken in optically bright conditions (200 or more array undershoots per second). The calibration results shown here will degrade under optically bright conditions. Primarily, resolution will broaden, and RMF trigger efficiency (threshold) function may shift to higher energies. Users should apply this calibration with care for conditions outside of near-dark conditions. Extending these results to higher optical loading is a top priority.

Point-like or off-axis nature of target. All of the results here are based on an on-axis point-like response. This is not a diffuse ARF or RMF. For targets up to 1.5 arcmin from the optical center, we understand that throughput changes are small (few percent) and not energy dependent.

Areas Still to Improve

We know this release is not perfect. We believe that this release will be useful for many astronomers analyzing data from point sources. However, we will be making improvements in the future to enhance the applicability of the products to more cases. Here are some areas:

- NICER tools that compute an observation-specific RMF and ARF based on conditions, including optical loading
- NICER tools that combine multiple per-module RMFs/ARFs into a single RMF/ARF for use in spectral analysis
- Off-axis and diffuse sources
- Applying energy-dependent systematic errors

Files Delivered

The following files are available

- Energy scale (gain) in CALDB
  - gain/nixtiflightpi20170601v005.fits (“optmv10” energy scale)
  - gain/nixtiflightpi20170601v006.fits (“optmv11” energy scale)
- ARF in CALDB
  - arf/nixtiaveonaxis20170601v004.arf (“consim135p” on-axis full-array sum of 52 modules)
- ARF in auxiliary delivery
  - nicer-arf-rmf-xti20200722.tar.gz (per-module ARFs for “consim135p”)
- RMF in CALDB
  - rmf/nixtiref20170601v002.rmf (“6s” full-array average of 52 modules)
- RMF in auxiliary delivery
  - nicer-arf-rmf-xti20200722.tar.gz (per-module RMFs for “6s”)

Practical Usage

Recalibrating Energy Scale

For practical usage, users are expected to both re-calibrate the energy scale of their data, and then use both RMF and ARF together. An analyst must use all three components (new energy scale, RMF, ARF) to gain the benefit of calibration improvements. Not using all three may lead to worse, and possibly catastrophically worse, results.

The easiest way to re-calibrate the energy scale is to re-run nicer-l2 on each observation data set, and then re-select data based on the preferred filtering criteria.

```
nicerl2 indir picalfile=nixtiflightpi20170601v006.fits ...
```

The above command tells nicerl2 to perform its standard processing but use the new energy scale calibration file for the PI column. The "..." indicates that you can use any of your own custom filtering criteria. Here “v006” indicates the “optmv11” energy scale.

You can also take an existing NICER cleaned event file and "recalibrate" it without re-doing all of the other NICER processing steps.

nicerpi infile_cl.evt hkfile=NONE calfile=nixtiflightpi20170601v006.fits outfile=outfile_cl.evt column=PI recal=YES

The above command will apply the new calibration to the existing event file infile_cl.evt, and write the result in outfile_cl.evt. However, you need to beware of one important issue. If your infile_cl.evt file has been screened in energy, then the bottom-most 1-2 bins of outfile.evt will be incorrect.   If you need these bins for science, the only way to recover these bins is to re-run nicerl2 as described above. However, if you performed a more generous selection during the cleaning phase, you can simply "ignore" them within XSPEC.

Using the ARF and RMF

The new ARF and RMF files can be used directly within XSPEC with no modifications, assuming you understand the caveats above.   A standard cleaned event file has 1501 bins, corresponding to 0-15 keV. The RMF files provided also have 1501 bins.

The ARF and RMF are matched together. Do not try to use the new ARF with an older RMF or vice versa. This is because the photon energy spacing has changed with the new responses, and both energy grids have to match.

The ARF and RMF files are one-per-module, as well as a 52-module array combination, designated as "array52". Typically, if you selected data from all 52 detectors, you should use the "array52" file. If you excluded some detectors, see the next section.

The new RMFs have the low energy trigger efficiency curve applied (low energy threshold curve). Going below about 0.4 keV, the trigger becomes less and less efficient, and that efficiency curve has a known shape. Because the trigger efficiency has been applied, you should be able to perform spectral fitting down to about 0.25 keV (assuming your data were taken in optically dark conditions - undershoots less than 50 ct/s). If you include data with brighter optical conditions, limit your fits to 0.4-10 keV.

What to Do If You Selected Fewer Than 52 Modules?

Many astronomers may wish to exclude certain detectors in their final spectrum. Typically this is because of certain detectors that are more noisy, such as DET_IDs 14 or 34. It is possible to handle this situation.

Please see the following web page for more information about how to retrieve and use per-module responses.

https://heasarc.gsfc.nasa.gov/docs/nicer/analysis_threads/arf-rmf/

Performance

Figure 2 shows the array-total performance of the model described below for the Crab nebula+pulsar.

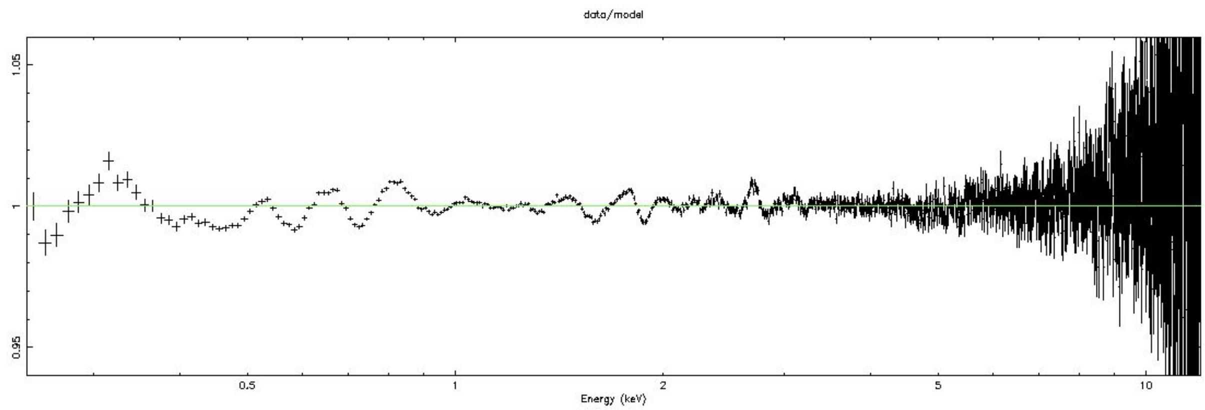

Figure 2. Residuals after using calibration release xti20200722 with the Crab Nebula.

The data are from observations 10130101ss where ss ranges from 01-32. Only optically dark (undercounts < 50ct/s) and low background conditions were chosen, using the standard low background criteria of nimaketime.

The following features are notable

- The energy range extends from 0.24 keV to 12 keV in this residual plot
- Residuals are <2% over the entire energy range
- Residuals are <1% rms over the entire energy range
- No gold or silicon features are visible
- The remaining features below 6 keV are systematics dominated, which justifies adding a systematic error of ~1% to all (bright) target spectra
- Parameters appear to be within "sane" ranges

Crab Reference Model

One big change from previous releases is that the astrophysical model of the Crab nebula + pulsar has become more sophisticated. The two big areas of improvement are

- inclusion of the as-measured absorption edge fine structure for Oxygen, Neon, and Iron (Kaastra et al. 2009)
- inclusion of a dust-scattering term (Smith Valencic & Corrales 2016)

The absorption model is basically the model of tbvarabs (Wilms et al 2000) as found in XSPEC. However, we have taken the edge fine structure as measured by Kaastra et al. 2009 using XMM gratings and embedded it into a new XSPEC model called **tbvarkrabs**. This external XSPEC model is distributed with the calibration products and you can use it to verify its performance. **This model is only meant for use with the Crab. Do not use tbvarkrabs with other targets!**

The dust scattering model is based upon Smith Valencic & Corrales (2016), which is embodied within the 'xscat' model of XSPEC. The xscatm model has recently been extended to be applicable to the NICER aperture size of 200 arcmin in radius, courtesy of Randall Smith.. xscatm **can be used for all NICER bright sources**. Set the aperture size to 200' to replicate the results shown here.

Summary of Model

The XSPEC model used here is embodied within crab/model.xcm. Here are the major terms of the model:

model TBvarkrabs*xscatm(curv*powerlaw + crab_pulsar)

- tbvarkrabs is the Crab-adjusted version of the tb(var)abs model most commonly used for XSPEC ISM absorption work
- xscatm is the dust scattering model of Smith et al. (2016), extended to larger aperture sizes
- powerlaw is the main power law continuum emission of the Crab, as modified by "curv"
- curv is an mdefine'd model representing curvature of the nebula in the <10 keV range as described by Kaastra et al. (2009)
- crab_pulsar is an mdefine'd model representing the spectrum of the pulsar itself, as described by Kaastra et al. (2009)

The curv model represents that the nebula has a spatially-dependent spectral shape. Kaastra et al. (2009) develop an empirical model of the Mori et al. (2004) Chandra Crab observations. The crab_pulsar model is an empirical formula presented by Kaastra et al. (2009), based on data from Kuiper et al. (2001). Both of these models have adjustable parameters, but they are kept fixed at the values established by Kaastra et al. (2009).

Note that Kaastra et al. (2009) present XMM-Newton grating observations in the 7-30A (0.4-1.77 keV) range. Their observations are most powerful to establish the absorption by the ISM, especially the fine structure around the Oxygen (0.533 keV), Iron (0.71 keV), and Neon (0.87 keV). They will be less powerful to establish broad-band spectral values like NH or power-law index. We have kept these broad parameters free to vary during spectral fits of NICER data. Abundances of individual elements, including Oxygen, Neon, and Iron, were allowed to vary and appear to be roughly consistent with Kaastra's work.

Below 0.4 keV there may be more uncertainties than above that energy. The Kaastra et al. (2009) work limits their fit to 0.411 keV and higher in energy, except for examining the column density at the Nitrogen edge at 0.4 keV. We have little information about the fine structure profile of the ISM near the Carbon edge near 0.285 keV. Also, the trigger efficiency curve and off-diagonal "shelf" response terms are surely correlated below 0.35 keV, and we are unlikely to have gotten a perfect match to all data. For that reason, we expect systematic errors to be larger (~5%) below 0.4 keV.

Above 10 keV, we have assumed the power law index 2.105 continues to higher energies without turning over. We have adjusted the total instrumental throughput above 10 keV to satisfy this assumption. However, the assumption may not be perfectly correct, and the >10 keV response is quite likely to have a more complicated behavior than a simple multiplicative correction. Thus, we expect systematic errors to be in the 10% range above 10 keV. For most observations that are background-dominated above 10 keV, these considerations won't matter in any case.

Changes and Improvements

RMF

RMF work has been a collaboration with Jack Steiner, who originally adapted the RMF code from the work of Scholze & Procop. We have made some additional changes to accommodate NICER-specific details. Since we distributed the xti20200202 ("Calibration Summit") products, here are the changes that made it into this release.

Recall that the RMF deals with both resolution and redistribution of photon energy into counts. The resolution part is what analysts normally think of for the RMF, which is the spread of counts around the main photopeak. However, there are also redistribution effects which create very broad features that essentially are flat all the way down to low pulse heights. I.e. a 6 keV feature can produce apparent "shelf" counts between "0 eV" and 6 keV; typically, the counts in the shelf are at much less than a few % of the photopeak level. We have been refining the model of both resolution and redistribution.

"Back side" changes. We are now aware that at energies >9 keV, the 500 um silicon detectors are optically thin enough that photon interactions near the backside of the detector produce more redistribution "shelf" than we were expecting from the basic Scholze & Procop model.

- Change: improved model of escape peak and shelf for input photons >9 keV, tuned to BESSY ground-based data.
- Effect: the RMF shelf increases by a factor of about 2. The xti20200202 products will under-predict the shelf by this factor. This mainly will be relevant only for sources that are extremely hard, bright, and heavily absorbed, so that many high-energy photons are

converted to low pulse heights. For soft or faint sources, the low-energy photopeak will dominate over the shelf.

"Front side" changes. The Scholze & Procop model appears to underpredict redistributed shelf counts for photon energies in the 0-1.8 keV range (below the Si K edge). We are adjusting for this after the fact.

- Change: enhance the shelf for photon energies 0-1.8 keV by ~1.6x.
- Effect: The xti20200202 products will under-predict the shelf by a ~2x factor. This will show up for highly absorbed spectra, and the energy range will depend on nH. The attenuation due to nH will cause a drop of counts toward low energies, but the measured counts will be much more than the model. For the Crab, with nH=3.5e21, the current Team model under-predicts by a factor ~2 in the energy range 200-400 eV. For GX 301-2, nH ~2-4e23, the underprediction should be about the same, but much more visible up to 0-600 eV.

Resolution changes. The model of how the FWHM of the photopeak is simulated has been changed.

- Change: more physical Fano-like model of resolution is applied.
- Effect: not clear, probably minimal for typical users. However, the new approach will allow us to store a single "master" RMF and broaden it for each detector based on its intrinsic resolution.

Application of Trigger Efficiency Curve. The trigger efficiency curve is present in this release. That means fitting down to ~0.25 keV is possible. Jack Steiner has made "private" RMF releases with the trigger efficiency curve applied, and this release is similar, except that trigger efficiency parameters have been tuned to the new optmv10 energy scale, and to the Crab.

- Change: trigger efficiency curves applied to RMFs.
- Effect: now possible to fit down to ~0.25 keV.

Overall changes. Based on the above changes, Jack Steiner also performed a "re-fit" of the model to pre-launch data taken at BESSY. These resulted in changed model parameters.

- Change: RMF parameters more closely match pre-launch BESSY data.
- Effect: small changes in redistribution throughout the energy band. ("Small" is probably few percent, but the effects will be highly dependent on spectral shape and absorption.)

ARF

There are no functional changes to the process of making an ARF. However, since the RMF and energy scale have changed, the ARF parameters were "re-tuned" to match the Crab data. The spectrum used as a reference is described above. Therefore, the ARFs will be numerically different.

- Changes: small adjustments to ARF to compensate some of RMF effects.
- Effects: spectra above 9 keV will probably have small, ~5%, changes.

One part of the process is to fit a correction spline to the array-sum Crab spectrum, assuming it maintains a pure power law to high energies. The correction reflects the deviation of the best fit with known physics of reality. The correction curve is included in the released data, as arf/nicer-consim135p-teamonly-corr.arf. Note that the value is the fractional correction as a function of energy. Figure 3 shows the spline fit correction curve.

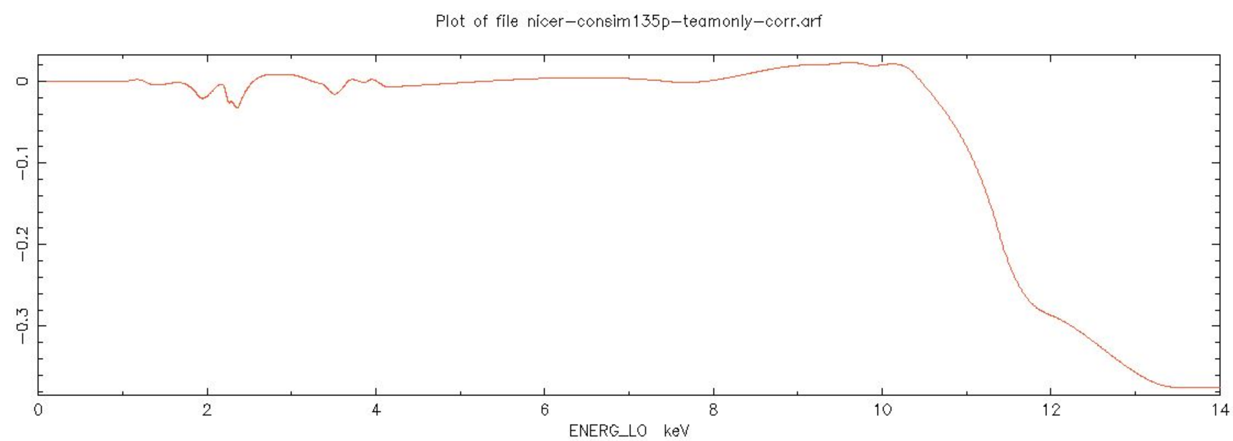

Figure 3. NICER spline correction function for the full 52-detector array in the 0-14 keV band for calibration release xti20200722.

As you can see, below 10 keV, the correction is very small. Above 10 keV, there is a significant adjustment that must be made to match the Crab data. We do not understand this result completely. However, the simple X-ray scattering model we are using may not work well at higher energies. The fact that a "kink" in the curve shows up around 11-12 keV – the Gold L edge region - indicates that the total X-ray concentrator throughput is not well modeled there.

Still, below 10 keV, the model matches the data quite well, and the spline correction is small. Figure 4 zooms in to this region more closely.

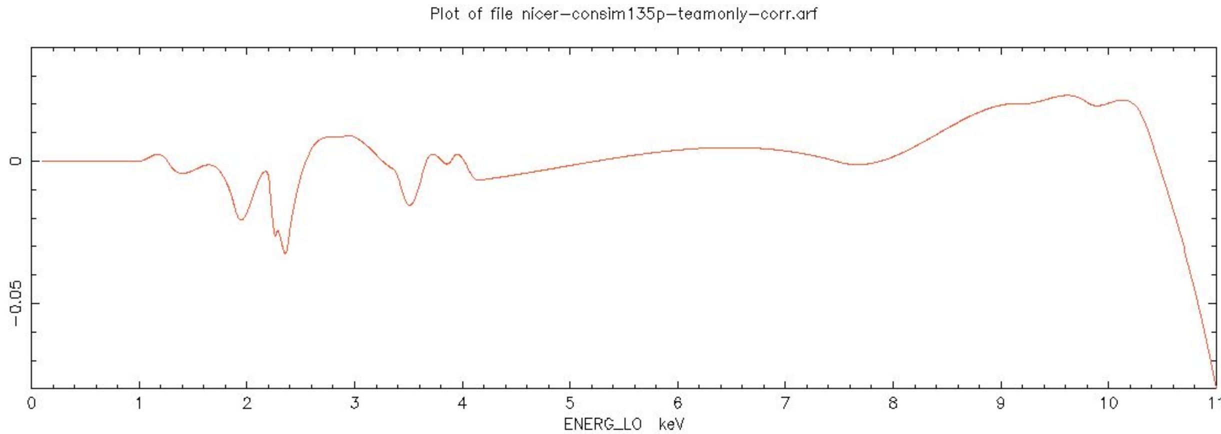

Figure 4. Same as Figure 3, in the 0-11 keV range.

Below 10 keV, the largest corrections are around the gold M edge. This edge is actually a complex, with fine structure features near 2.2 keV, 2.7 keV, 3.5 and 4.5 keV. Some of these features are evident within the correction applied. The peak-to-peak correction in that region is about 4%. These corrections indicate that the gold reflectivity model (which is taken from the Hitomi reflectivity calibration work; Kurashima et al. 2016) is not perfect.

The feature between 1.8-2 keV represents imperfect modeling of the Silicon absorption edge. This feature was not present in the version 1.02 RMF release, so it appears to be a small modeling error in the RMF.

There are several broad-band features in the 4-10 keV range, which we interpret to be imperfect modeling of the total mirror throughput.

Energy Scale (Gain)

Compared to the xti20200202 (“Calibration Summit”) release, we have found some additional issues in the current energy scale solution in the range 0.5-3 keV. The problems show up as small wiggles in the energy scale, especially in the 1-2.5 keV range. Adjusting for these produces a new energy scale, designated as "optmv10” and “optmv11”.

- Change: adjustments to the energy scale to be more continuous. Up to 5 eV change at E=0.53 keV (O K edge) and <5 eV at 2 keV. Thus we are still (barely) maintaining our promise of better than 5 eV gain solution in the NICER energy range.
- Effects: the wiggles in the energy scale were absorbed in the ARF calculations, at least for sources with a Crab-like spectrum. These were typically ~2% in the 1-2 keV range and about 3% in the 2-3 keV range.
- “optmv11”: reduce long-term drift of zero-point by about 50% based on 3 years of trend data. The net effect is a difference of about 0.15 eV/yr in long term shift.