NICER CALIBRATION: Release Notes of xti20210707 (optmv12, response calculators)

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Version 1.1 2021-07-19 - revised for adjusted trigger efficiency centroids (pre-release)

Introduction

This document describes developments and performance of NICER Calibration release xti20210707. This release contains improvements of:

- Energy scale solution “optmv12”
- Support for new ARF and RMF response calculators

Summary

This file documents NICER calibration products released as CALDB xti20210707. Summary of results:

- Crab residuals <2% in range 0.24 - 14 keV
- Revisions to energy scale (optmv12), which extends gain performance for undershoot counts in the range 0-500 undershoot count/s (compared to 0-200 in previous releases)
- Files to support ARF calculator ‘nicerarf’
- Files to support RMF calculator ‘nicerrmf’

Example residuals are shown in Figure 1.

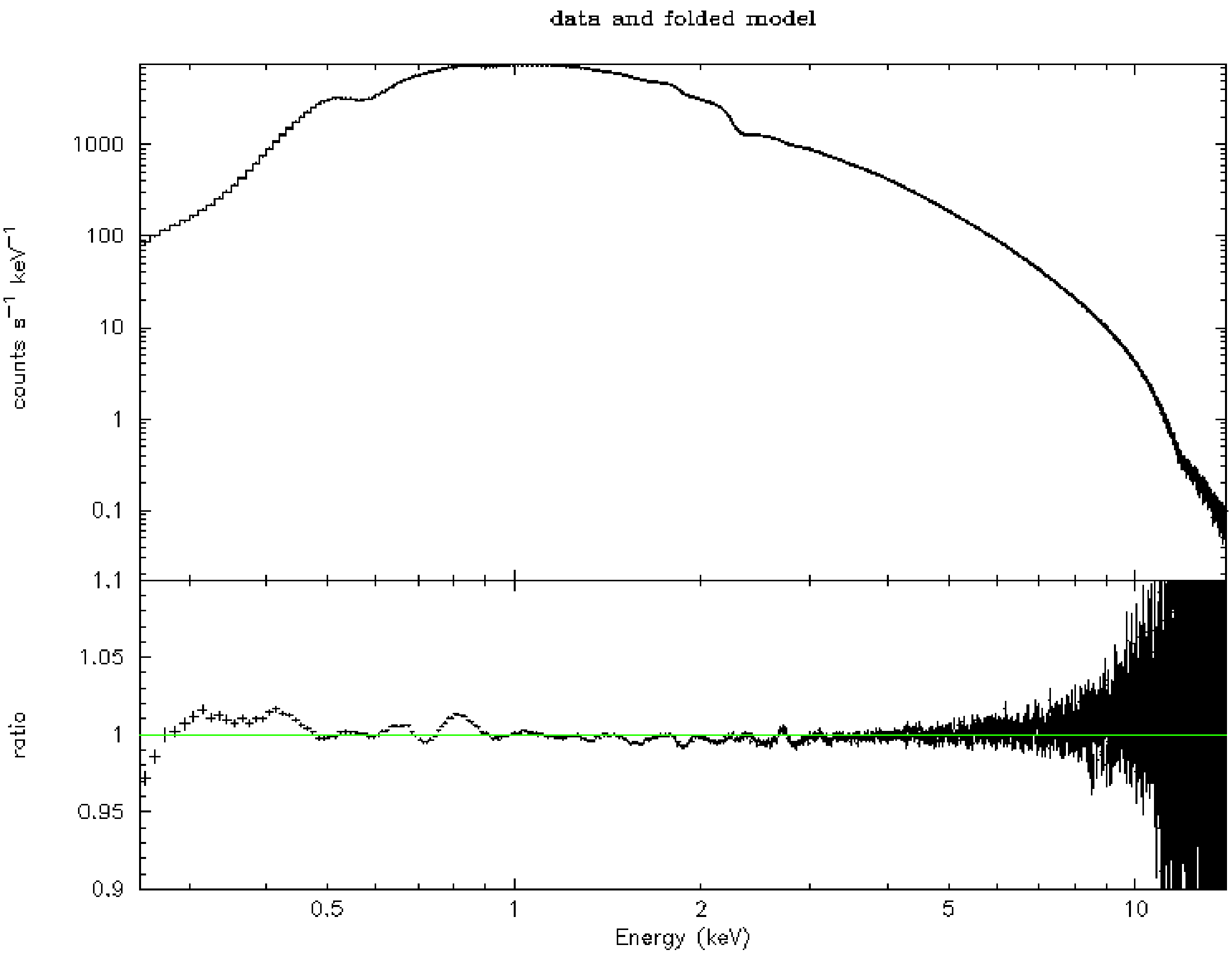

Figure 1. Example residuals after fitting the Crab Nebula using NICER calibration release xti20210707.

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. Please note that with this release, performance for on-axis sources has not changed significantly. The major improvement is for off-axis targets, and for sources with high optical loading.

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.

Off-Axis Performance. We expect that for sources within 100 arcseconds of on-axis (ANG_DIST < 0.0278), performance should be comparable to on-axis results. We are aware that the current off-axis model has special deficiencies for energies above 8 keV and off-axis angles of >150 arcsec. Response errors may be 100% or more. Users of the response calculators should be especially careful of off-axis targets that have high energy tails.

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 included 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). However, because of the new optmv12 gain and response calculators in this release, we can now recommend calibrated results in the range of 0-500 undershoot ct/s. Optical loading will broaden the energy response as well as modify the trigger efficiency parameters, and these effects are taken into account in the RMF calculator.

Point-like or off-axis nature of target. The NICER response calculators in this release are capable of calculating the response to point-like as well as diffuse sources. The possible diffuse surface brightness profiles supported are: gaussian, uniform flat sky, and user-specified radial surface brightness profile.

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:

- Applying energy-dependent systematic errors
- Low energy response (< 1 keV)

Files Delivered

The following files are available

- Energy scale (gain) in CALDB
  - gain/nixtiflightpi20170601v007.fits ("optmv12" energy scale)
- ARF in CALDB
  - arf/nixtiaveonaxis20170601v005.arf (on-axis full-array sum of 52 modules only for simulation purposes)
- Auxiliary files used to compute ARF by 'nicerarf'
  - alignment/nixtixrcalignparam20170601v003.fits - per-module alignment and tip angle
  - vignette/nixtivignette20170601v001.fits - off-axis vignetting profiles per shell
  - xrcparam/nixtioffareashell20170601v001.fits - on-axis effective area per shell
  - xrcparam/nixtixrcshellparam20170601v003.fits - per-module and per-shell throughput and roughness parameters
  - detqe/nixtidetqe20170601v001.fits - detector quantum efficiency curve
  - dettran/nixtidettran20170601v001.fits - detector entrance window transmission curve
  - xrctran/nixtixrctran20170601v001.fits - XRC thermal shield transmission curve
  - xrctran/nixtixrccorr20170601v002.fits - XRC spline correction curve
- RMF in CALDB
  - rmf/nixtiref20170601v003.rmf (full-array average of 52 modules only for simulation purposes)
- Auxiliary files used to compute RMF by 'nicerrmf'
  - rmfbase/nixtirmfbase20170601v001.fits - "base" RMF used as template by nicermf
  - detparam/nixtipidetparam20170601v001.fits - per-module resolution and trigger efficiency parameters (slow channel)
  - detparam/nixtipifastdetparam20170601v001.fits - per-module resolution and trigger efficiency parameters (fast channel)
- Additional files delivered
  - detparam/nixtinoiseparam20170601v001.fits - per-module noise peak parameters

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 (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 nicerl2 on each observation data set, and then re-select data based on the preferred filtering criteria.

```
nicerl2 indir ...
```

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. There should be no need to manually specify the picalfile parameter if one is using an updated version of CALDB.

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=CALDB 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

NICER now supports computing a per-observation ARF and RMF response file using the ‘nicerarf’ and ‘nicerrmf’ task. These responses will be tuned to the conditions of your specific observation and spectral extraction. Please see software documentation on the NICER website for more information about how to use these response calculator tasks.

The 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 mismatched 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 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?

Using the NICERDAS software released with HEASoft 6.29, the number of modules enabled/disabled or selected/deselected is handled automatically. The software uses a portion of the event file called the “FPM Selection” information which contains detector exposure information on a per-detector basis. This information is used by ‘nicerarf’ and ‘nicerrmf’ to compute accurate responses.

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.

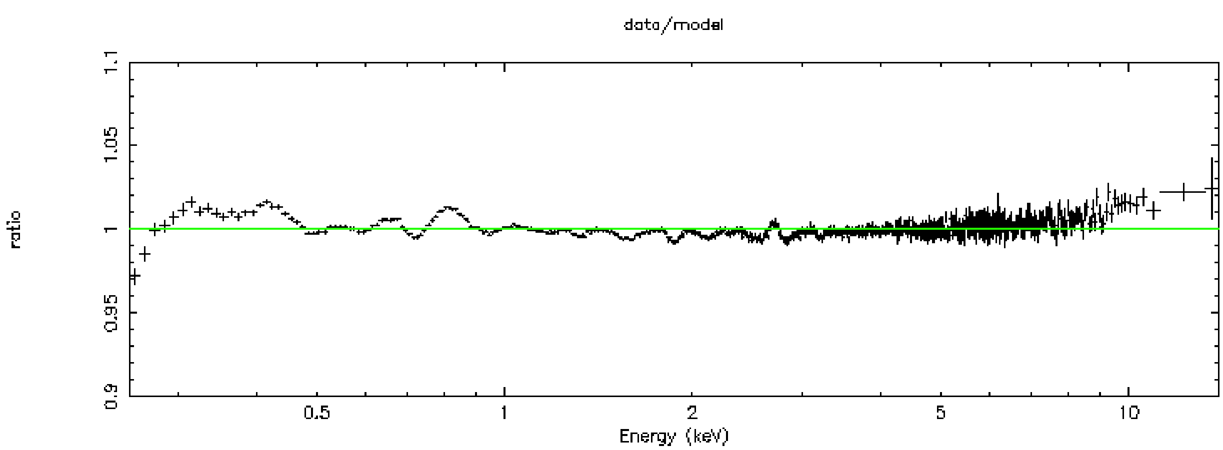

Figure 2. Residuals after using calibration release xti20210707 with the Crab Nebula.

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 15 keV in this residual plot
- Residuals are <1.5% in the 0.4-10 keV range described above in the Domain of Applicability
  - Residuals are larger below 0.4 keV, but still within the specified 10% uncertainty limits
  - Above 10 keV, residuals are still within the 10% limits established above
- No strong 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

There are no changes to the fundamental physics of the RMF generation. RMF work has been a collaboration with Jack Steiner, who originally adapted the RMF code from the work of Scholze & Procop.

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.

What has changed is the mechanics of how the RMF is calculated. In the previous release (xti20200722), the response was pre-calculated and the user was expected to combine responses by hand. With the new response calculator 'nicerrmf' the response is calculated based on the specific observing conditions of the observation and spectrum in question. The primary driver of changes in the response are optical loading, which causes the response matrix to broaden. In addition, the trigger efficiency curve is known to move slightly in energy space under high optical loading conditions. These effects are now handled by nicerrmf.

- Change: new 'nicerrmf' RMF calculator
- Effects: no changes for typical observation, but improved performance for large undershoots (> 200 undershoot count/s)

ARF

This is a major change to the ARF generation process. Previously, the ARF was delivered as a set of pre-computed files that the user was expected to combine by hand. With this release, this is performed automatically.

The primary drivers of ARF variability are the off-axis angle, which may vary moment-by-moment depending on NICER's pointing control; and which detectors are active at a given time, which can also vary over time. NICER's ARF calculator tool takes these effects into account when it generates a custom ARF.

A large amount of calibration work was undertaken to compute off-axis ray-tracing profiles, vignetting profiles, and to estimate the alignment and optical tip-tilt of each module. The results of these efforts are stored in calibration files as described above.

As shown above, performance in the 0.4-10 keV band has not changed since the previous release. However, some degradation within the 0.25-0.3 keV band is evident; but still within the 10% limits established in the Domain of Applicability section above.

- Change: new 'nicerarf' ARF response calculator
- Effects: no change in the 0.4-10 keV range (<1.5%); slight degradation in the 0.25-0.3 keV range is evident but still within the specified limits described above

Energy Scale (Gain)

This release contains the "optmv12" gain revision. The primary driver of this release is to extend the range of applicability to higher optical loading conditions. Compared to the previous release, which was recommended to screen undershoots in the range 0-200 undershoot count/s, the new optmv12 release recommends an enlarged range of 0-500 undershoot count/s. This should allow users with more extreme conditions to analyze their data. For example targets within 45-60 degrees of the sun, as well as more daylight conditions.

- Change: extend optical loading calibration to the range 0-500 undershoot count/s
- Effects: no change for previous calibration range of 0-200 undershoot count/s (<3 eV); large improvement (up to 40 eV) in the range 200-500 undershoot count/s