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GAIN CALIBRATION MEMO

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ABSTRACT

This memo presents data from the latest gain calibration using the *NuSTAR* on-board calibration source. We have found a time-dependent change in the energy scale of the *NuSTAR* detectors. Based on our analyses we recommend that users with data from late 2013 onwards that were processed with a CALDB version earlier than 20150316 reprocess their data with the new calibration files. After this calibration has been applied we recommend that users quote a systematic error of ~ 40 eV at energies near 6 keV and ~ 60 eV near the 68 keV ^{44}Ti lines.

1. INTRODUCTION

2. DETECTOR GAIN CALIBRATION

Each *NuSTAR* focal plane contains a calibration source primarily composed of ^{155}Eu which has several prominent lines at high (86.54 and 105.4 keV) and low energies (6.06 and 6.71 keV). The source is located on a movable arm that can deploy the calibration source into the field of view so that we can confirm the gain of the instrument in flight. We obtained two epochs of calibration source data: one just after observatory commissioning in June 2012 and one after the prime mission completed in January 2015. The initial values of the CALDB files were determined using extensive pixel-by-pixel-by-grade calibration of the detectors on the ground (Kitaguchi *et al.* 2011). We used the first epoch of calibration data to fine-tune the "CLC" and "FPM_Gain" CALDB files based on the in-orbit conditions of

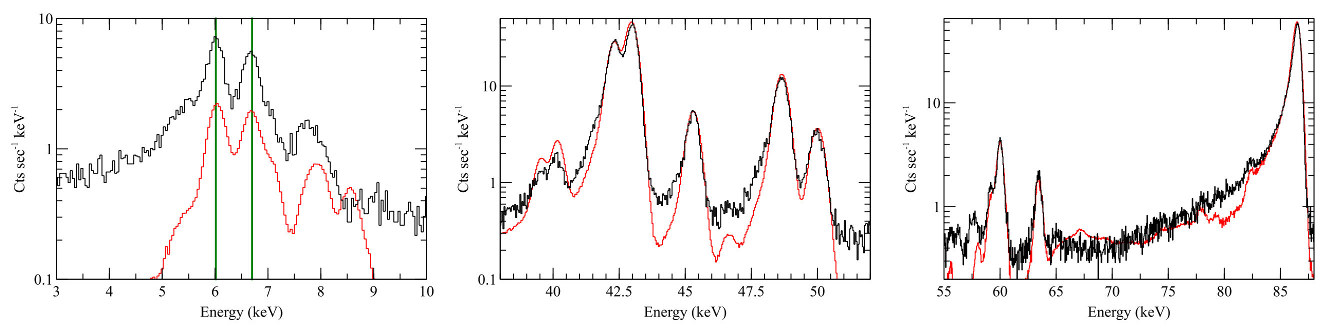

FIG. 1.— Representative spectrum of the calibration source for FPMB Det 0 (black) compared with the spectral model of the calibration source convolved through the instrument response (red, see text). Left: the lowest energy lines along with the locations of the 6.07 and 6.71 keV X-ray lines in the calibration source (vertical green lines.); Middle: The 35 to 55 keV bandpass; Right: the 55 to 88 keV bandpass containing the main 86.54 keV line.

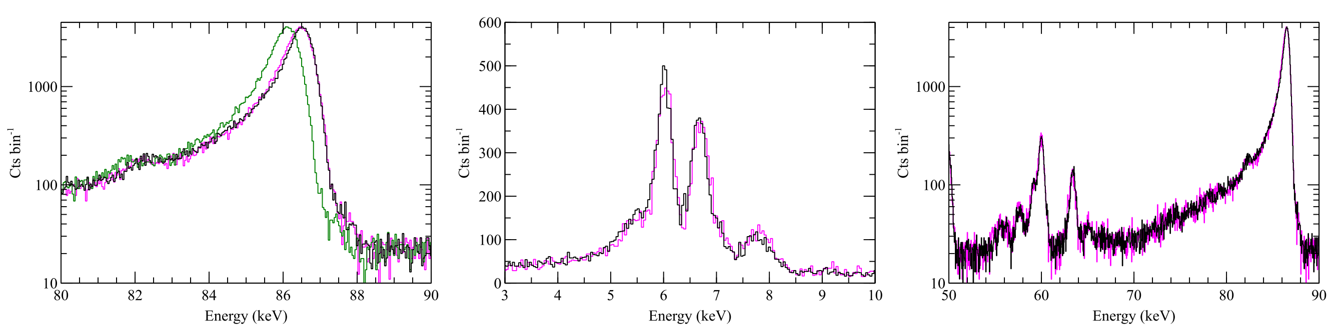

FIG. 2.— Representative spectrum of the calibration source for 2012 epoch FPMB from detector 0 (black) compared with 2015 epoch data from the same detector. Left: A zoomed comparison of the region near the 86.54 keV line show the 2012 data (black) and the 2015 data before (green) and after (magenta) the time-dependent correction has been applied. Middle: A comparison of the 2012 (black) and the corrected 2015 data (magenta) at low-energies; Right: A comparison of the 2012 (black) and corrected 2015 (green) data across the 55 to 88 keV bandpass.

TABLE 1
GAIN-CORRECTIONS (2012-VS-2015)

Detector Number	A Slope	A Offset (eV)	B Slope	B Offset (eV)
0	0.9944	-60	0.9964	-59
1	0.9928	-66	0.9939	-56
2	0.9999	-34	0.9937	-34
3	0.9977	-55	0.9963	-7

the instrument.

For details of how the pipeline uses these files, please see section 3 in the NuSTAR Data Analysis Software Guide at the following location:

`http://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf`

As we have limited on-orbit data, we determine the "CLC" corrections for each detector (e.g. integrated over all pixels) separately for grades 0, 1, 2, 3, and 4 (corresponding to one- and two-pixel events) and as a block for grades 5 through 8 (three-pixel events) and a single correction for grades 9 through 20. We used the second epoch to introduce a time-dependent gain correction in the FPM_gain CALDB file that takes out an apparent ∼0.2% per year shift in the gain as well as a residual small shift in the zero-point offset of the energy scale (hereafter "slope" and "offset", respectively) using the following equation:

$$E_{new} = \frac{E_{old}}{Slope} - Offset\,. \tag{1}$$

We compare the first epoch data to a reference model spectrum to determine the absolute energy scale corrections required (if any) using Equation 1. We constructed a GEANT4 model of the calibration source during ground calibration and produced a simulated spectrum based on the blend of Eu isotopes contained in the calibration source. We multiply this input spectral model by an absorption curve based on the attenuation material between the calibration source and the detectors (primarily the Beryllium entrance windows to the focal plane) and then convolve the result with the detector response matrix (RMF) stored in the CALDB. This results in a "counts" spectrum that can be directly compared to the observed spectrum to test for changes in the energy scaling.

We fine-tune the CLC parameters by performing a fit over a change in the slope and the offset and minimizing the resulting chi-square value. The resulting model fits result in large reduced chi-square values (> 5) owing to the large offset between the model and the observed spectrum at low energies (the result of an unmodeled spectral component likely due to the Compton scattering of gamma-ray photons in the detectors) and small differences in the shape of the 86.54 keV line (only statistically significant due to the large number of source counts near 86 keV). However, the line centroids that we recover are accurate across the *NuSTAR* science bandpass from 3 to 79 keV (Figure 1). Iterating this analysis (e.g. applying the correction and then re-fitting the "new" observed spectrum to the model spectrum) results in residual fits with slope values typically within 2e-4 of unity and offset values within 40 eV of zero.

We note that the *NuSTAR* data are binned to a native resolution of 40 eV, so the fact that we find residual offset errors on that scale is likely evidence for some aliasing. We therefore recommend adopting systematic errors of 40 eV on the offset and 2e-4 on the slope. This implies a systematic uncertainty of 40 eV at energies near Fe emission features in the spectrum and a systematic uncertainty of ~ 60 eV near the 67.86 keV line used for the analysis of ^{44}Ti (40 eV uncertainty in the offset combined with ~ 20 eV due to the uncertainty in the slope at 68 keV).

Using the second epoch of calibration source data we can determine if there is a long-term trend in the gain of the instrument. We do this by comparing the 2015 epoch data to the 2012 and adjusting the energy channel (PI) value and minimizing the chi-square value between the two distributions. Again, subtle changes in the line shape with time near the 86 keV line and the large number of counts in that line result in a reduced chi-square value that is formally unacceptable (and therefore make it impossible to quote formal statistical errors on the fit parameters). However, we do find by visual inspection that the adjusted 2015 spectra do match the 2012 at all energies (Figure 2)). The corrections required to scale the 2015 up to match the 2012 epoch observations are found in Table 1. We note that, as above, once these corrections are applied we find residual fits with slopes within 2e-4 of unity and offsets within 40 eV of zero, so we consider these the residual uncertainties on this fitting method. The time-dependent gains are implemented in the standard NuSTARDAS pipeline. As of this writing we assume that the time-dependence in linear and can be interpolated between the 2012 and 2015 data sets and can be extrapolated beyond 2015. Future epochs of calibration source data will determine if this is correct.

3. IMPLEMENTATION

The 20150316 CALDB release contains the calibration information described above. The time-dependence was already implemented in the *nucalcpi* FTOOL and so no changes to the NuSTARDAS code was required to implement these changes.

4. SCIENCE IMPACT

This gain shift should primarily be seen in analysis of the ^{44}Ti lines. Depending on the strength of the source, this gain shift can also produce artificial “absorption” features in the residuals. This is cause by a mismatch in the energy of the observed counts and the energies in the ARF. The ARF contains edges near 10 and 12 keV; if a gain shift of 40 eV is present then these may appear as artificial “absorption” or “emission” features. We note that these features are weak and so will only be seen in sources with extremely high signal-to-noise. Additionally, we note that shifting the energy scale may also cause an artificial “soft excess” in the data (below 4 keV). This is caused by a mismatch in the energy scale and the steep “detabs” absorption curve introduced by the optics thermal covers, Beryllium windows, and detector absorption layers. The significance of this is highly dependent on the steepness of the source spectrum so we cannot make a blanket statement about whether or not this soft excess will be present in all data sets. Again we do note that this will likely only be present in data sets with high signal-to-noise and/or where there is an overlap with a soft X-ray instrument.

5. RECOMMENDATIONS

We do not expect this calibration to have much impact on data from the first half of the prime mission (before mid-2013). For users with data from late 2013 and on we do recommend reprocessing the data using the new calibration files, especially if the source produces high signal-to-noise and/or the science user is attempting a joint-fit with a soft X-ray observatory.

REFERENCES

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