CalibrationStatus/EnergyScale

Title: BAT Energy Scale and Resolution

Revision Date:	2017-10-04
Version:	3
Document:	SWIFT-BAT-CALDB-ESCALE-v3

1. Summary

This document describes the BAT energy scale and resolution. Since launch, the gain scale has varied from nominal by as much as 5.5%, but more typically 4.3%. With this release the BAT team has provided updated gain scale every six months of the Swift mission, from start to current date of release. Within three years after Swift's launch, the array-average gain drifted by about 3-4% from the pre-launch value, corresponding to about 2 keV centroid shift at 60 keV. More recently, the array-average gain has remained nearly steady at about 4% from its pre-launch value.

2. Component Files

File Name	Valid Date	Release Date	Version	Description
swbpulsecal*v001.fits	-	2017-10-04	1	Best linear DAC-to-energy conversion (every six months)
swbpulseflt20040101v001.fits	2004-01-01	2004-12-19	1	On-board linear DAC-to-energy conversion
swbquadres20030304v003.fits	2003-03-04	2005-03-18	3	Best non-linear pulser DAC-to-channel conversion

3. Scope of Document

This document relates to the computation of the BAT energy scale (pulse height to absolute energy). BAT events and survey data are typically tagged with a nominal energy based on the amount of charge deposited in the CZT detectors. This document briefly describes the chain of calibrations required to get an absolute energy scale.

4. Reason for Update

The BAT team has estimated the instrumental gain scale on a detector-by-detector basis, since the start of the mission. Previously, a single at-launch value was provided. With this release, scientific analysts can expect a slight improvement in reconstruction of the gain scale, which may lead to a slight improvement in coded mask sensitivity.

5. Discussion

An X-ray absorbed by a BAT detector produces a given amount of charge, that is collected by front end electronics and converted to a raw pulse height channel.

Thus, at its basic level, the energy calibration process involves knowing how much charge is deposited by a given energy X-ray photon. The process is complicated by using an intermediate scale (pulser DAC), and that the detector electronics are non-linear.

The BAT performs periodic on-board electronic calibration using a pulser. The pulser injects charge pulses of a reported amplitude into the electronics and measures the resulting pulse height channels. The pulser voltage (and hence charge), is controlled by a digital-to-analog converter (DAC). Thus, the raw pulse height scale can be tied to the pulser-DAC scale. During normal operations, the pulser-DAC to pulse height channel calibration is done at two different voltage points, forming a linear relation. This is the "gain-offset" map which is produced frequently by the instrument, and which should be available in each observation. This data is **not** stored in the calibration database, since it can potentially change over short periods of time.

This same process was done on the ground using many pulser voltage points. For almost all detectors, this produces a slight deviation from the linear relation, which is currently best fit by a cubic polynomial. This relation is stored on the ground as the "swbquadres*" CALDB file.

Having determined the pulser-DAC to channel relation, the pulser-DAC to energy relation must be found. This was done primarily by using ground calibration data from many different radioactive sources with known X-ray lines. The conversion may also be done with the on-board calibration sources (two ^{241}Am (Americium) tagged sources which illuminate the entire array). This linear relation is stored in the swbpulsecal* file in CALDB.

The Americium source produces a complex of lines corresponding to the radioactive decay of ^{241}Am and its resulting daughter products. The primary signature of the decay is a line at approximately 59.5 keV. In addition there is a complex of lines below 20 keV which correspond to X-ray emission by the Neptunium daughter product. Also, there are detector escape peaks in the 25-35 keV range. While the signature of Amercium decay is present a certain amount of cosmic X-ray background also survives the "tagging" process and is present in the spectrum. See the figure below for the typical spectrum.

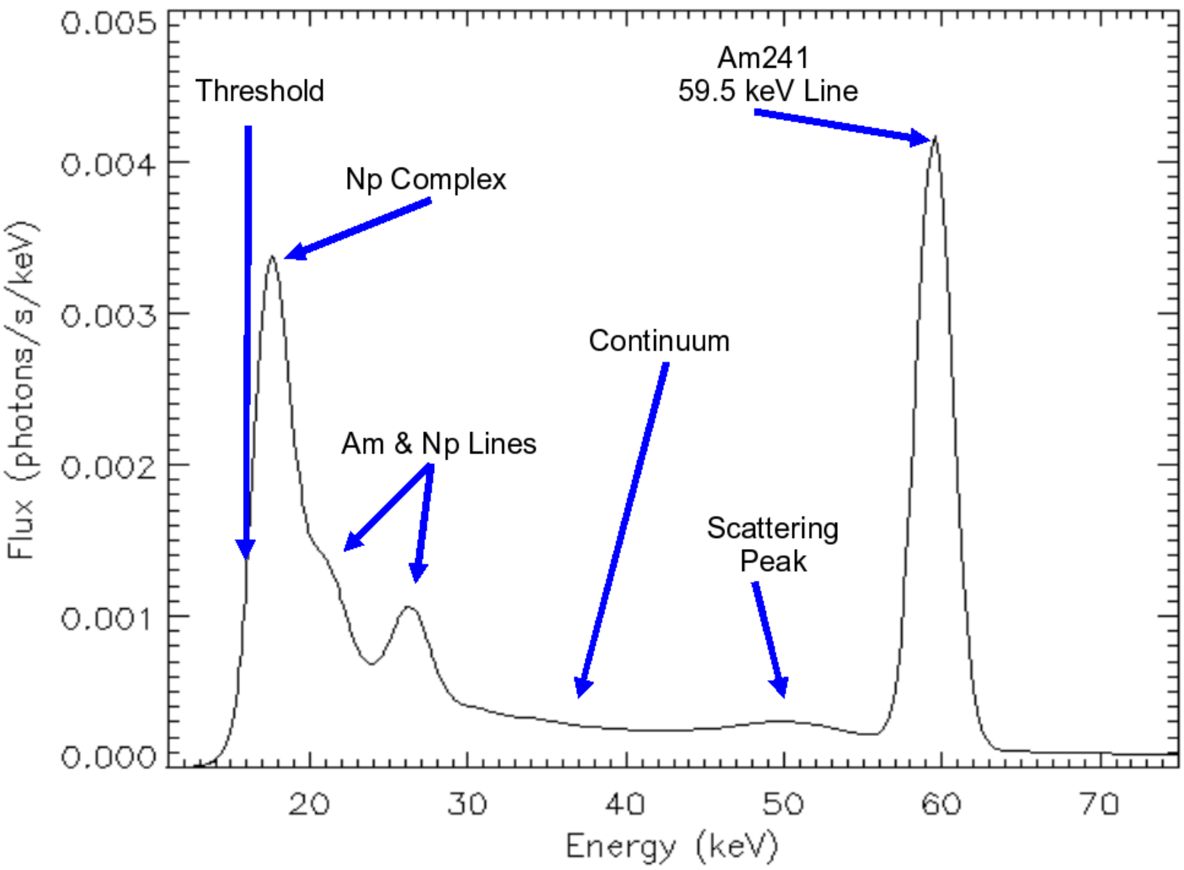

Figure 1. Model photon spectrum of a typical detector. The relevant lines and fitted features are labeled.

We continue to discuss the gain scale assignment process by considering survey data. The BAT on-board processing computes a nominal photon energy before binning the data. This nominal energy is based on a crude pre-flight linear relation. To determine a true energy-to-channel conversion for survey data, the flight conversion must first be backed out. This conversion is stored in the swbpulseflt* file in CALDB.

After launch, it is expected that the BAT gain scale may change slightly. Before this release, it was assumed that the gain did not change. However, with this release we demonstrate that the gain does indeed vary by approximately 5% over time.

5.1. Input Data

The BAT instrument periodically produces a calibration product known as the "Calibration DPH" or "Americium DPH." This product is a detector plane histogram (DPH), which is transmitted to the ground approximately once per hour. Unlike the normal survey DPHs, a calibration DPH is accumulated over a longer period of time, which may span multiple snapshots of a scientific target. Also, the DPH has different energy binning, which concentrates the spectral resolution around known calibration features, as shown in the figure above. These products are transmitted to the ground and stored in the trend data of the Swift archive.

The raw input data are heavily screened. Data are excluded for the following reasons:

- Data from known bad times are excluded, as defined in the swbbadtimes*.gti Calibration Database file;
- Data with problems indicated by DATA_FLAGS != 0 are excluded;
- EXPOSURE must be between 100 and 10000 seconds, to exclude short snippets of data as well as long exposures that might include bright targets;
- Gain and offset values should be in the normal range, to exclude times when the gain/offset calculation was out of equilibrium (usually after an instrument reboot);
- At least 4000 detectors enabled, to exclude times in safe hold or other off-nominal conditions;
- Count rate must be between 0.003 and 0.0095 ct/s/det, to exclude off-times as well as high background times;
- Exclude noisy detectors, using an algorithm similar to bathotpix;

Even with these screening criteria, typical exposures are between 1.0 and 2.3 Megaseconds for each detector, resulting in a spectrum with very high statistical quality.

5.2. Analysis Technique

Data are partitioned into six-month groups to improve the statistical quality even further. A spectral model is used to fit the relevant features of the calibration source as well as the X-ray background. As BAT is being used in non-imaging mode here, we include the effects of off-diagonal scattering as a phenomenological bump below the photo-peak as shown in the figure above.

The spectral model also contains parameters for per-detector gain, offset, and spectral resolution. We initially considered both linear gain change as well as offset as fitted parameters. However, initial analysis has not been able to detect any offset variation. Therefore, we fix the offset at its pre-launch value, and fit only the gain coefficient. This number can be expressed as the percentage variation of the gain from 100% for the 59.5 keV line, where 100% indicates the centroid of the line is exactly at 59.5 keV. This process was performed for each detector with valid data.

Also as a result of the analysis, we produce a new swbpulsecal* file for each six month interval. As input to bateconvert and baterebin, this is one of the key inputs that refines the BAT gain scale, and is the new Calibration product seen by users.

5.3. Results

Generally speaking, the fitting process went smoothly and produced valid gain results for all detectors. For detectors that were disabled for a significant period time, the last good value is reported and carried forward in time until a new value could be determined (if any). Generally this is satisfactory because detectors that were disabled for gain determination purposes were also disabled for scientific purposes, so there is no loss of scientific utility.

The following figure shows the overall gain shift of the BAT instrument on a detector by detector basis since launch.

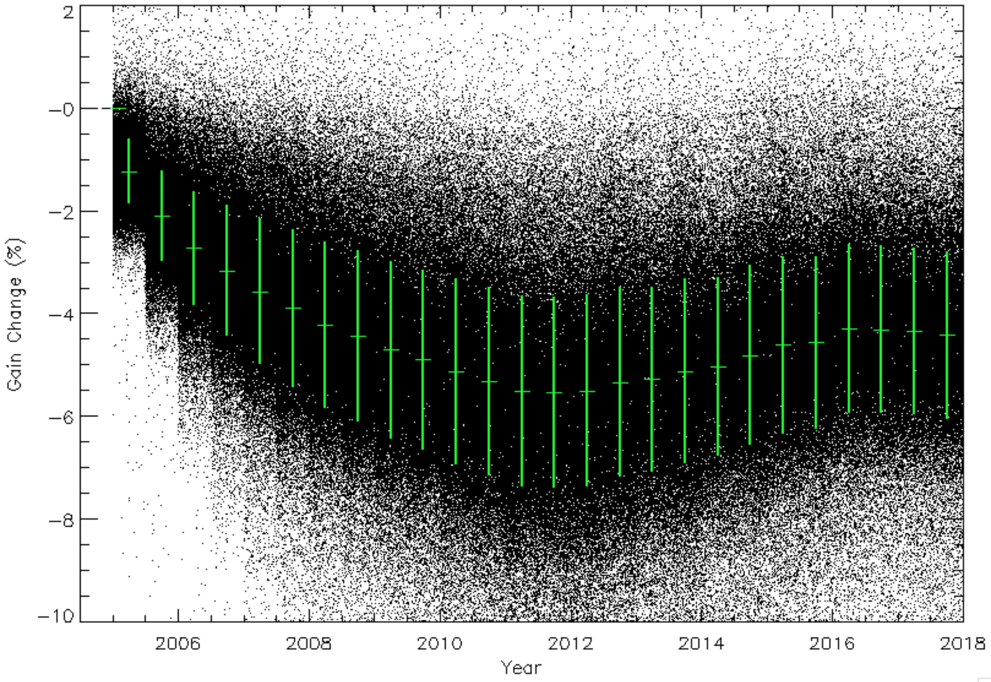

Figure 2. Overall gain shift of BAT instrument during the Swift mission lifetime, relative to 100% at launch. Each black dot is a gain shift measurement for a single BAT detector in that six month interval. Note that detectors have been given a random offset of up to 6 months to spread out the values so they can be more easily displayed. The green points with error bars are the six-month average and standard deviation of gain shift.

Note that the gain changed significantly during the first few years after launch, and has since stabilized. The BAT array-average gain shift has a maximum of -5.5% since launch, which occurred in the year 2012. Since that time, the average gain has actually recovered somewhat to about -4.3% shift since launch.

This does reflect the array average gain shift. On a detector by detector basis, some extreme detectors have shifted by -10% or more. Thus, the 59.5 keV Am241 line could appear at about 53 keV. However, these detectors are on the extreme end. The standard deviation of detector gain about the mean shift is approximately 1.8%, or about 1.0 keV r.m.s.

5.4. Interpretation

The gain has varied in a significant fashion since Swift's launch. One does not expect the BAT gain scale to remain 100% fixed over time. The BAT instrument is exposed to varying conditions in the space environment which can lead to gain changes.

Temperature is likely not a factor. Overall the temperature of the relevant XA1 digitizer is stable to fractions of a degree Celsius. In any case, we have seen no evidence that the spacecraft systems have experienced a long term temperature drift comparable to the gain drift seen.

Radiation damage is likely to be a factor. High energy sub-atomic particles in the space environment, especially the SAA, routinely irradiate the entire spacecraft, including the detectors and electronics. High energy nuclei have enough kinetic energy to displace atoms in the detector from their crystal lattice positions, which introduce lattice defects. These defects act as charge traps which reduce the amount of charge collected for a given X-ray. Radiation damage occurs largely in the SAA, which is altitude dependent.

It is remarkable that the gain shift has recovered somewhat over the past 5-6 years from its maximum excursion to present. Based on laboratory tests, there is some evidence that room temperature crystal defects can heal over time. Since launch Swift's mean orbital altitude has descended from about 590 km starting in 2012, to about 553 km in late 2017. Although this seems like a small decrease, in fact the SAA strength decreases steeply with altitude, and is expected to be a factor of 4x or more smaller compared to the launch altitude. Thus, the radiation damage rate has likely decreased significantly since 2012, which correspond to the time frame when the gain shift stopped growing worse.

5.5. Impact to BAT Data Analysis

A gain shift of about 5% will affect BAT scientific results to some degree. Compared to the values previous used (a constant gain value for each detector), a 5% shift will correspond to a distortion of the energy scale of input spectra by that much. A Crab-like spectrum changes by about 10% in flux at 60 keV between before and after the improved gain solution is applied. Put another way, the power law index derived before and after this new gain solution is applied would shift by about -0.03. This is typically smaller than the quoted uncertainty for Swift BAT-detected gamma-ray bursts, and is typically smaller than one would consider theoretically meaningful.

The change in gain scale also affects the assignment of line-like features. The line centroid would shift by about 5% compared to the previously published values. The energy width would increase by about 1.8%. Since the detection of line-like features has not been credibly claimed for BAT data of GRBs, we do not consider this to be a significant factor.

In addition to the overall bias, there is a per-detector r.m.s. scatter of ~1.8% about the array mean. For survey analysis, a mis-assignment of gain will correspond to assigning a photon at the edge of a bin to the wrong survey bin. In other words, the ~1 keV error in energy assignment for an X-ray at 51 keV may push that event down into the 25-50 keV bin instead. This will lead to non Poissonian detector-to-detector variations which degrade the BAT survey sensitivity.

Let us briefly estimate the impact to sensitivity. The predominant contribution to the BAT count rate is the X-ray background of about 0.33 ct/s/det, or 8 Crab units. After applying the mask weighting, imaging artifacts are typically 1% of the peak amplitude, or about 8 Crab x 1% = 80 mCrab. However, not all counts are misassigned. We consider that the fraction of counts shifted is proportional to the fractional energy shift due to gain drift relative to the fractional energy bin size for the survey. For a four-bin survey with logarithmic-spaced bins (the default), delta-E/E = 66%. For an eight-bin survey, delta-E/E = 33%. Thus, the residual coding error for the shifted counts would be about 80 mCrab x (1.8/66) = 2.2 mCrab for the four-bin survey, and 4.4 mCrab for the eight-bin survey.

The amount of exposure required for this energy shift coding error term to be dominant over statistical noise is between 500 ksec and 700 ksec. This level of exposure exceeds by a factor of 10x-20x the maximum exposure of any single Swift observation sequence. Thus, the gain shift will be important for survey analysis only when summing multiple observation sequences which are non-co-pointed, for example when doing an all-sky survey. The BAT team has used a temporally dependent gain shift correction for all all-sky survey analyses since 2009, and recommend the same for other efforts.

5.6. Calibration Files

The "swbpulse*" files give the linear conversion coefficients between pulser voltage (in DAC units) and the energy of photons that produce those voltage pulses. These coefficients are different for each detector, so these files give the coefficients for all 32768 detectors.

The "swbpulsercal" file contains the "correct" best-known coefficients. In previous deliveries, this file was based upon ground calibration. Now, these quantities are based on in-flight data. A new file is produced each six month interval since launch.

The "swbpulseflt" file contains the coefficients that are being used by the flight software. At the present time, the flight software uses a set of pre-programmed coefficients based on pre-launch data. The swbpulseflt file is used by bateconvert to "back out" the improper conversion performed in flight and the swbpulsecal* file is used to apply the proper conversion. At some future time, a new table may be uploaded to the flight software with the correct values. When that time comes, a new swbpulseflt calibration file will be added which will be identical to the swbpulsecal file. It is expected that this will somewhat improve the energy assignment made by bateconvert.

The "swbquadres*" file gives the cubic conversion coefficients between pulser voltage (in DAC units) and the channel in which those pulser voltages are centered. The name "quadres" is really a misnomer now, since the coefficients it contains are no longer quadratic (but rather, cubic) nor are they coefficients of the residuals (but rather, of the full conversion equation). The name has been kept the same in hopes that it will lead to less confusion than changing it would.

5.7. Usage

The BAT calibration files take advantage of the Calibration Database's capability to index files by time. The standard tasks bateconvert and baterebin will automatically query the Calibration Database (CALDB), based on the observation time of the input data file, and retrieve the correct gain correction files. Thus, no additional action is required by the user other than to download the new BAT CALDB files and install them properly.

5.8. Testing

The BAT team has tested preliminary versions of the gain calibration for several years. Overall, the new gain coefficients have performed well.

5.9. Example results

Users must use the following tools to obtain the correct energy scale:

1. `bateconvert` for event data (i.e. GRB data).
2. `baterebin` for binned data (i.e. survey DPH data).

Both of these tools apply a detector-dependent energy shift which accounts for the non-linear behavior of the detector electronics, as well as detector-to-detector offset shifts not currently accounted for by the on-board automatic calibration.

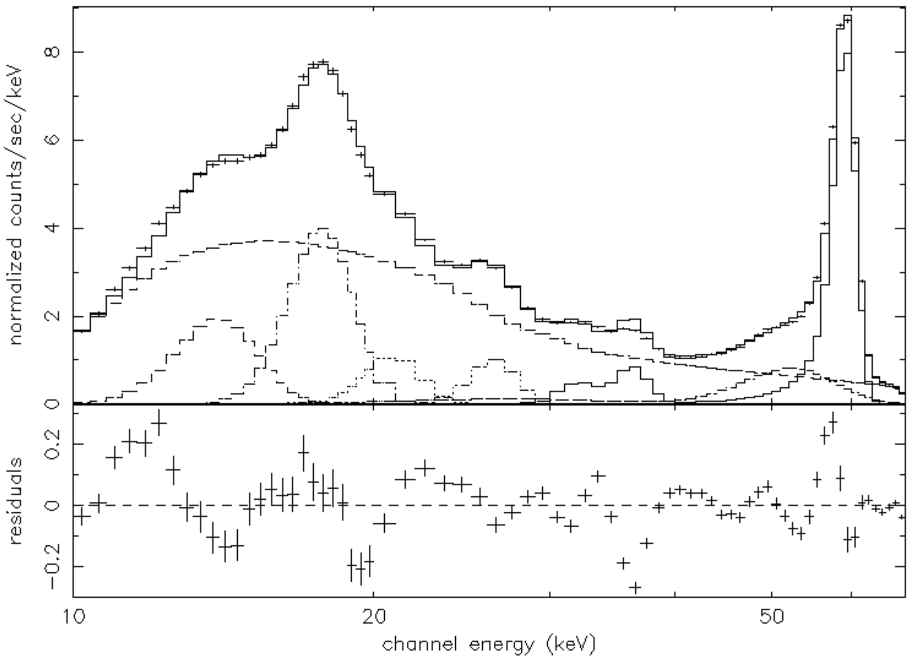

Figure 3. On-board calibration spectrum of the ^{241}Am source. The features include: ^{241}Am lines at 59.5 keV and 26.3 keV (with exponential tail); escape peaks for Cd and Te at 26.7 and 32 keV; L X-ray lines from Np at 14 and 17.75 keV; and a power law representing the sky background.

Figure 3 shows an on-board calibration spectrum with identified lines.

When no gain correction is applied, users can expect +/- 3 keV errors (90%, with maximum errors of 10 keV), and increased noise in detector images due to detector-to-detector gain variations.

With correction, users can expect +/- 0.3 keV errors. The Figure shows the on-board calibration spectrum after correction. The line centroids are consistent to within 0.1 keV, and the widths are consistent with the broadening derived by ground calibration.

6. Energy Resolution

As described above, and in Figure 3, the resolution is as expected from modeling of the ground calibration data. For example, the FWHM of the ^{241}Am line at 60 keV is <4 keV.

7. Caveat Emptor

Please use the newest software and calibration files, since these contain improvements to the energy scale. For event data, it is worthwhile to re-apply the correction since the SDC may not always be using the most recent software or calibration files.

8. Expected Updates

The BAT team can provide additional updates as warranted. It is expected that the gain will vary slowly. After the initial rapid change in gain between 2005 and 2011, the overall gain now changes by less than 0.5% (r.m.s.) in each six month interval.

9. Version History

9.1. Update 2017-10-04

```
* swbpulsecal20??????v001.fits

   New time-dependent gain solution.  New swpulsecal*.fits files produced at
   six month intervals (on January 1st and July 1st).
```

9.2. Update 18 Mar 2005

```
* swbpulsecal20030101v003.fits
* swbquadres20030304v003.fits

    This pair of files contains new voltage-to-ADU conversion coefficients,
```

```
    including a new FULLCUBIC cubic model, derived from ground calibration
    data.  These files apply to observations at all times.  They
    DEPEND ON BUILD 14 SOFTWARE.
```

9.3. Updated 19 Dec 2004

```
Overview
   * One new file, swbpulseflt20040101v001.fits, is introduced
   * This file is *required* for Swift build 11 analysis

swbpulseflt20040101v001.fits

    NEW FILE TYPE.  Contains actual on-board pulser DAC to energy
    conversion coefficients.  The current file contains the default
    per-sandwich average coefficients.

swbpulsecal20030101v002.fits
swbquadres20030304v002.fits

    New versions, based on improved knowledge of electronic pulser
    and energy calibration.
```

last edited 2017-10-05 11:56:06 by CraigMarkwardt