CalibrationStatus/PositionUncertainty

Title: BAT Position Uncertainty

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Version:	2
Document:	SWIFT-BAT-CALDB-CENTROID-v2

1. Summary

This document describes the BAT position uncertainty, based on instrument alignment. Also a discussion of the instrument alignment map is provided.

2. Component Files

BAT Aperture

File Name	Valid Date	Release Date	Version	Description
swbaperflux20041120v001.fits	2004-11-20	2005-09-08	1	Reduced aperture for flux measurement **RECOMMENDED**
swbaperture20041120v002.fits	2004-11-20	2005-09-08	2	Complete aperture map for detection
swbaperedge20041120v001.fits	2004-11-20	2005-09-08	1	Aperture edge map
swbaperture20030101v003.fits	2003-01-01	2005-09-08	3	Complete aperture map - pre-launch data only

BAT Teldef

File Name	Valid Date	Release Date	Version	Description
swb20041120v001.teldef	2004-11-20	2004-12-24	1	Post-launch **OBSOLETE**
swb20021001v002.teldef	2002-10-01	2004-12-24	2	Pre-launch data only
swb20041120v002.teldef	2004-11-20	2007-09-13	2	Launch default value
swb20041209v001.teldef	2004-12-09	2007-09-13	1	Star tracker adjustment
swb20041213v001.teldef	2004-12-13	2007-09-13	1	Star tracker adjustment
swb20041215v001.teldef	2004-12-15	2007-09-13	1	Star tracker adjustment
swb20070828v001.teldef	2007-08-28	2007-09-13	1	Star tracker adjustment
swb20070904v001.teldef	2007-09-04	2007-09-13	1	Star tracker adjustment
swb20070911v001.teldef	2007-09-11	2007-09-13	1	Star tracker adjustment

BAT Distortion Map

File Name	Valid Date	Release Date	Version	Description
swbdistort20041120v001.fits	2004-11-20	2006-04-07	1	Initial release - Requires Swift Build 19

3. Scope of Document

This document relates to position uncertainties as determined using the BAT imaging system.

4. Reason for Update

Incorporate the teldef files that adjust for star tracker alignment changes.

5. Discussion

5.1. Aperture File

The BAT aperture is used for image deconvolution and mask weighting (ray tracing) operations. These are basic image operations that most users will need to perform in order to obtain positions and fluxes for any source. The BAT aperture file contains two components:

- aperture mask pattern (image)
- aperture alignment information (keywords)

The two components are combined by the software.

The aperture image is an array which indicates the positions of the lead mask tiles (-1 = tile; +1 = opening). The uncoded portions of the field of view (shielded regions) are indicated by a value of 0. The tile positions were chosen randomly. The aperture map in CALDB reflects the as-launched tile pattern.

The mask alignment information was determined as described below.

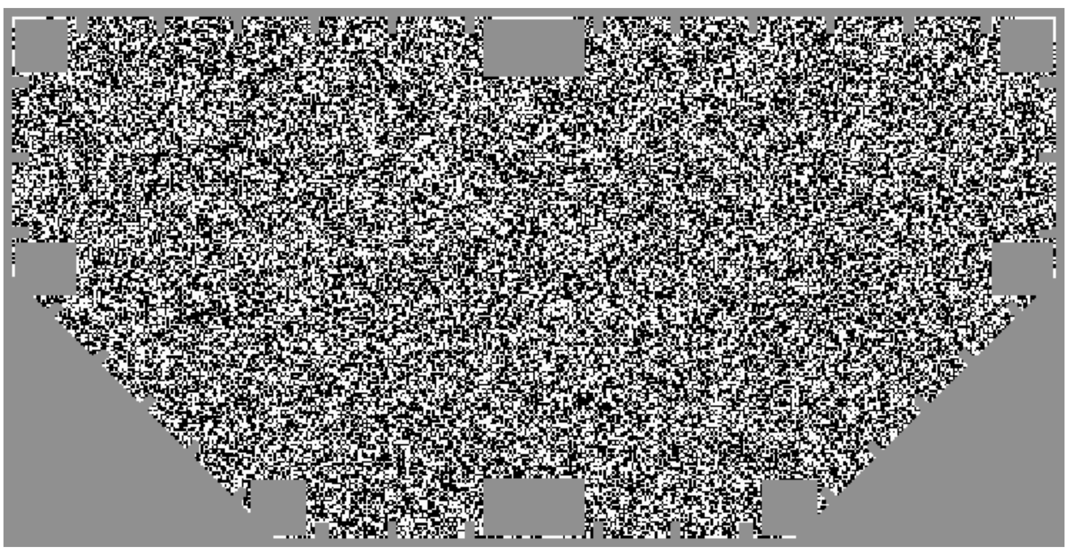

Figure 1. The full BAT aperture map. Black indicates a mask tile, white indicates an open cell, and grey indicates an uncoded region. Note the grey cut-out regions are areas used for the mask structural supports.

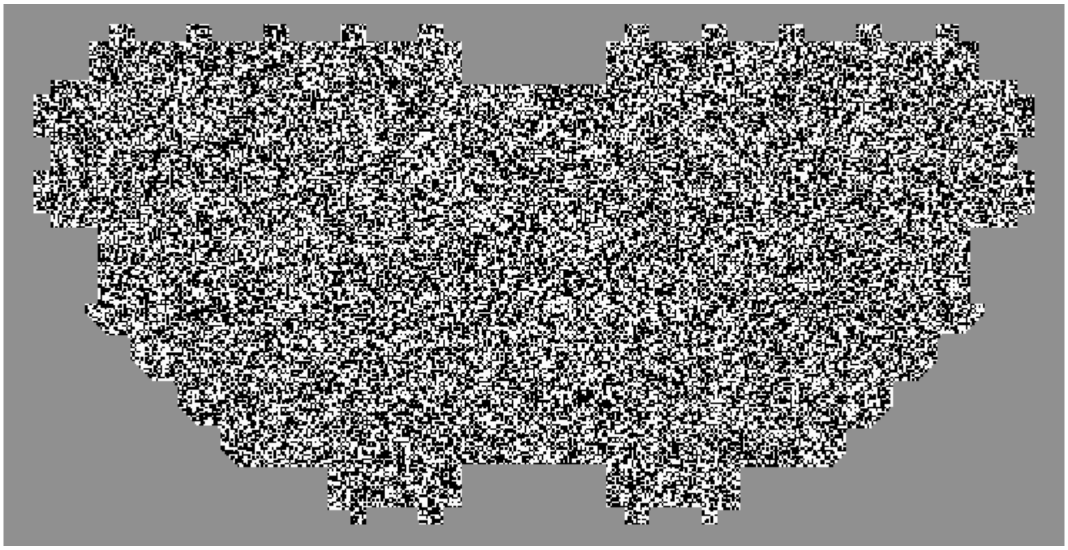

Figure 2. The reduced BAT aperture map, for flux measurements. Note that the uncoded regions are larger, and the mask region is reduced in size.

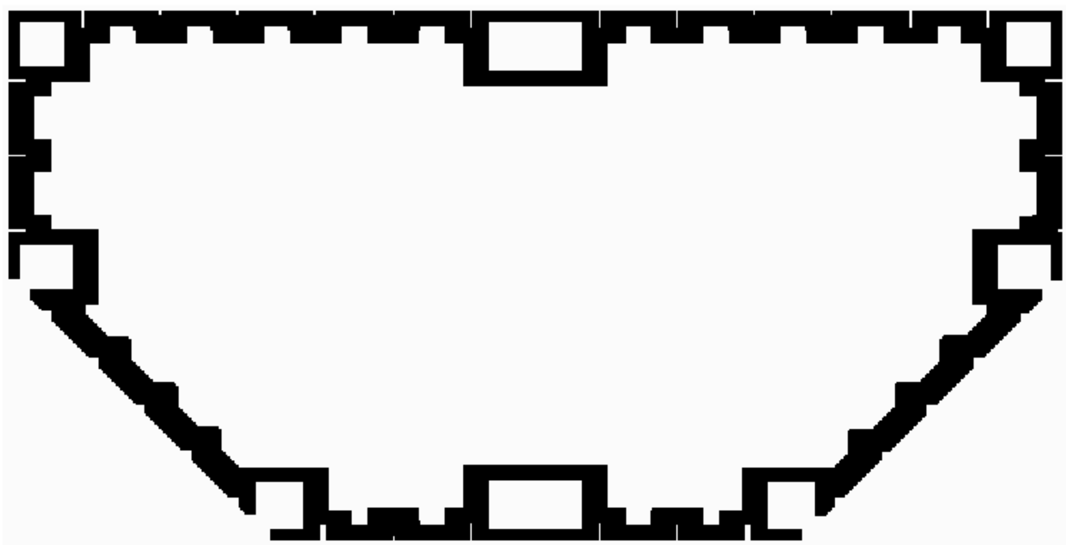

Figure 3. BAT aperture edge map. This map shows the "difference" between the full and reduced apertures.

Figure 1 shows the full aperture map. This is the complete mask as it was built and launched. However, the BAT team is now aware that there are imperfections at the edge of the mask, such as small openings in the fringe shield, and protrusions above the mask tile plane. These imperfections tend to degrade the image/flux performance for most sources, and thus it is desireable to remove them.

The BAT team devised a "reduced" aperture which will provide a more stable measure of fluxes and positions (Figure 2). This reduced aperture should normally exclude the portions of the array which are shadowed by known imperfections.

The difference between the "full" and "reduced" apertures is shown in Figure 3. The edge region shown is the portion of the mask which has been blanked in the reduced aperture. Users may need to use this map to blank out the corresponding regions on the detector array, since it may contain unmodelable features: fringe shield gaps, i.e. brightly illuminated detectors; and mask support structure shadows. The batmaskwtimg task can be used to ray trace the "edge" aperture onto the detector plane.

5.2. Choice of Aperture Files

Normally the **user should use the "reduced" aperture optimized for flux** ("swbaperflux"). This aperture should provide the most stable measure of the flux of a source. However, there are two reasons to use the full aperture:

- a marginally detected source at edge of field of view; or
- source outside the reduced aperture but inside the full aperture.

5.3. Teldef File

The "teldef" file is a "telescope" definition file. It describes how the BAT instrument is aligned with the spacecraft axes. The alignment quantities were determined by comparing the measured positions of known sources to their known positions, as described below.

5.4. Position Centroid Uncertainty

BAT positions are derived by generating a sky image using `batfftimage` and then fitting a point spread function to detected sources using `batcelldetect`. The BAT-to-spacecraft alignment was analyzed and checked using BAT observations detected in survey mode from approximately 2004-12-15 to 2005-01-15. The alignment data are stored in the BAT teldef and aperture files, and include rotation and focal length adjustments.

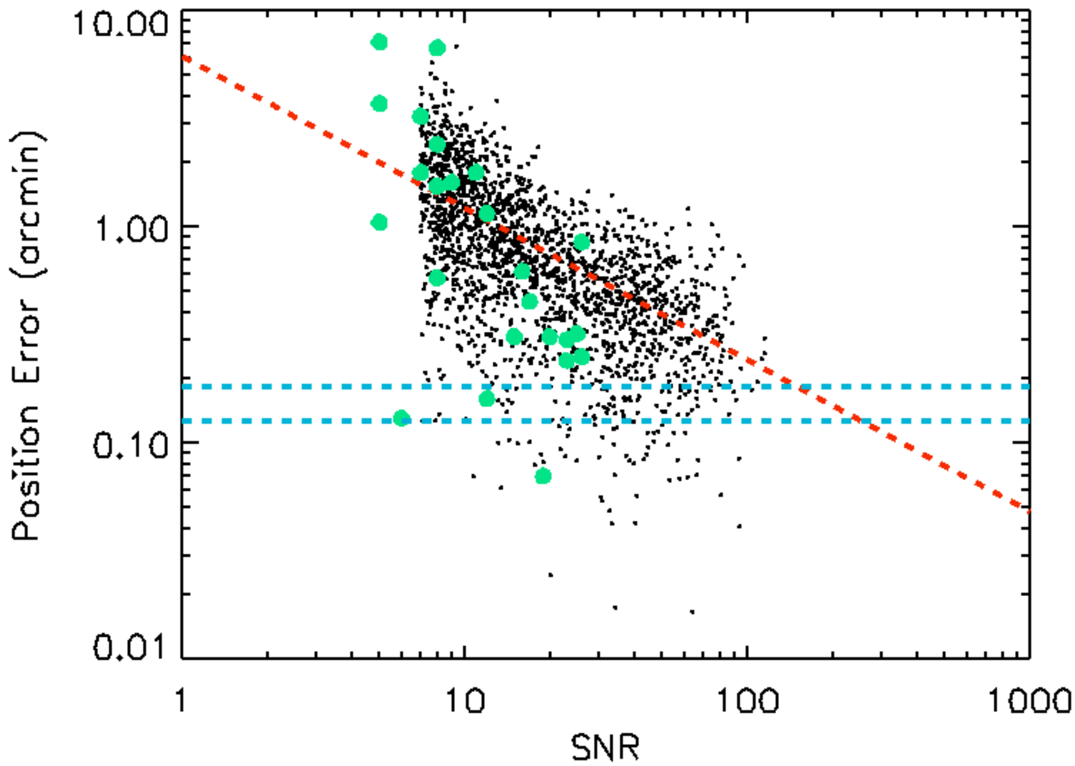

Figure 4. BAT position errors as a function of signal to noise ratio, for known sources. Both ground (black) and flight (green) determined positions are shown. The red line is equation 1 for K=1 (see below). The blue lines indicate approximate error contributions of annual aberration (top) and energy-dependent focal length (bottom), for a typical source 25^{o} off-axis (spectrally hard, power law with photon index -1.0.).

The residuals from the alignment calibration provide information on the centroiding error of the BAT. The residuals in Figure 12 were fit to a power law as a function of signal to noise. The best fit is:

```
ERR_RAD = K x 6.1 SNR^(-0.7)   [arcmin; radius]  (equation 1)
```

where SNR is the signal to noise ratio reported by either batcelldetect or the BAT position message sent by TDRSS. This function is applicable for 6 < SNR < 100, but is poorly tested for partial coding fractions of less than ~25%.

Table 1. BAT centroid uncertainty.

Confidence	K	10 sigma	20 sigma
68%	1.20	1.5'	0.9'
90%	1.79	2.2'	1.3'

95%	2.11	2.6'	1.6'
99%	2.86	3.5'	2.1'

For specific confidence limits, please use the values for K in Table 1. Also, representative error radii are given for 10 sigma and 20 sigma detections.

5.5. Star Tracker Alignment Changes

The BAT teldef file describes the transformation between the spacecraft body coordinate frame and the BAT instrument coordinate frame. From time to time throughout the Swift mission, the spacecraft body coordinate frame has been *redefined*. The BAT teldef file must also be adjusted when these redefinitions occur.

The Swift spacecraft body coordinate frame is an imaginary coordinate system whose +X axis is coaligned with the instrument axes. Thus, the +X axis might be called the spacecraft boresight direction, and the +Y and +Z axes defined the body roll angle about the boresight. The imaginary spacecraft axes are tied to real celestial coordinates via the star tracker, and the rotation between the two coordinate systems is known as the *star tracker misalignment quaternion*. The spacecraft axes essentially be redefined by adjusting the components of this quaternion.

Early in the mission history, the spacecraft boresight axes were adjusted to be primarily coaligned with the XRT axes. These adjustments occurred on 2004 Dec 9, 13, and 15. Later in the mission, the spacecraft boresight axes were readjusted to compensate for other attitude issues, related to problems with the on-board gyroscopes. These adjustments occurred on 2007 Aug 28, 2007 Sep 4 and 2007 Sep 11. The later changes reflected a *roll* of the spacecraft body axes and not a repointing of the look direction itself. There are BAT teldef files for each and every change in star tracker misalignment quaternion, for completeness's sake, even if no good BAT data might be present at those times.

Table 2. Log of Star Tracker Misalignment Changes.

Date/Time	VSACST1MISQ_1	VSACST1MISQ_2	VSACST1MISQ_3	VSACST1MISQ
Launch Default Values	0.10451703700	-0.69933982400	0.10451703700	0.69933982400
2004-12-09 15:06:08.7	0.10540161600	-0.69920705000	0.10540161600	0.69920705000

2004-12-13 00:07:40.7	0.10495934800	-0.69927357680	0.10495934800	0.69927357680
2004-12-15 02:03:41.1	0.10464802357	-0.69926510608	0.10527050932	0.69928200000
2007-08-28 15:09:49.0	0.10363084885	-0.69941747616	0.10425335847	0.69943343006
2007-09-04 17:46:43.0	0.10447850976	-0.69929060382	0.10510099959	0.69930731221
2007-09-11 20:11:27.0	0.10363084885	-0.69941747616	0.10425335847	0.69943343006

For reference, the star tracker alignment changes are shown in Table 2.

5.6. Distortion Map

As of Spring 2006, it is now known that there are small scale but systematic image centroid shifts as a function of position in the BAT field of view. Based on 9 months of data from 2004-12-15 to 2005-09-15, the measured positions of known sources were compared to the known positions. The position offsets were preserved in instrument tangent-plane coordinates, and grouped by position in the field of view.

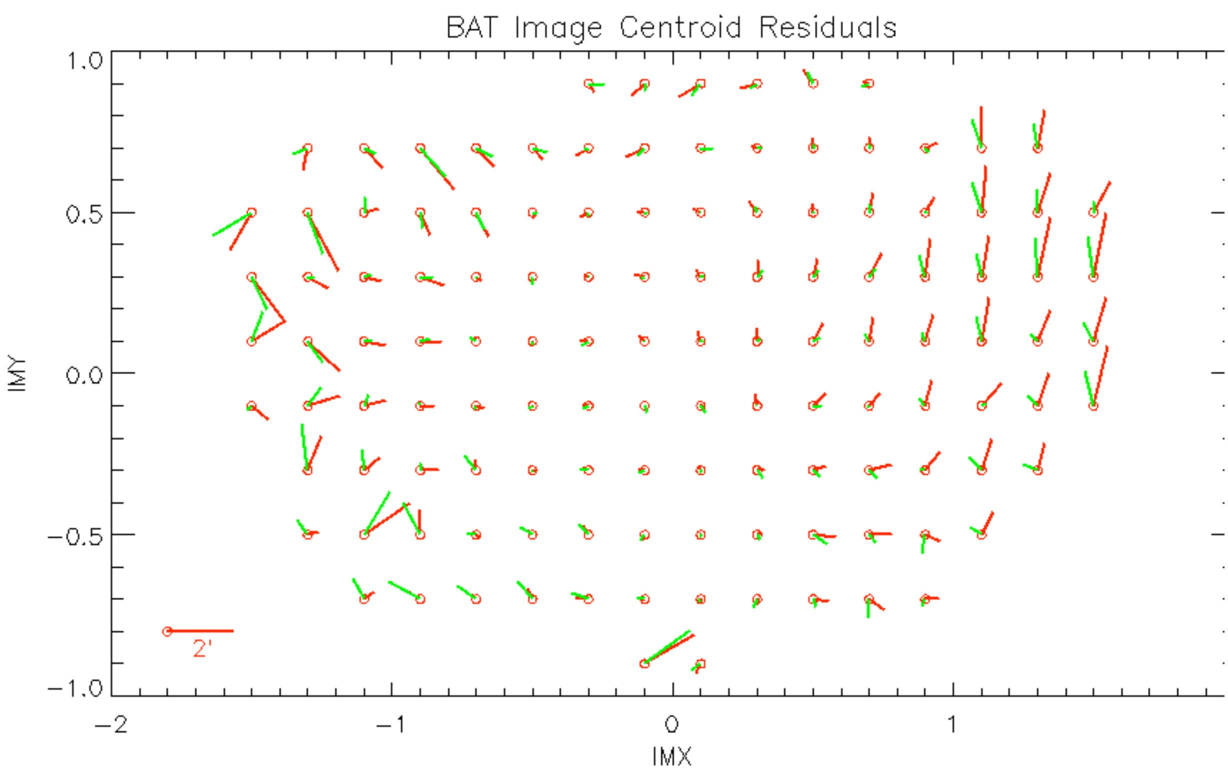

Figure 5. Position offsets as a function of image coordinates. The red lines show the measured position offset, while the green lines show the best possible solution using the aperture+teldef files alone (i.e. the distortion map is required). Coordinates are tangent plane coordinates (IMX and IMY). The vector indicates the offset from the expected (circle) to the measured (non-circle) positions, with the vector scale shown.

Figure 5 shows the resulting measured position offsets. This figure shows that beyond 45 degrees (IMR > 1), there are significant residuals, and within that angle, the residuals are negligible. The maximum residual offset is about 2 arcmin. Note that this effect is commonly only seen for very bright sources, or by averaging several faint source positions together.

The offsets appear to show a systematic but non-regular pattern. The current aperture+teldef model appears to help some, but does not remove the systematic offsets. Thus, a systematic distortion map was developed. This map is a thin-plate spline approximation to the measured offsets, which smooths over the noise in Figure 5, and interpolates between gaps. The resulting spline function is sampled on a regular grid and stored in the swbdistort* file. This file is used by source detection and mask weighting (ray tracing) tasks to produce more accurate fluxes and positions.

As a cross check, a sample of 63 BAT GRB positions were compared with known XRT counterpart positions (Moretti et al. 2005, A&A, 448, L9), both with and without the distortion map correction. There was a typical 10-30 arcsec improvement in the BAT position by using the distortion map. In a few cases, there was a slight degradation in the BAT position (< 10 arcsec), which would still be consistent with the statistical nature of the BAT positions.

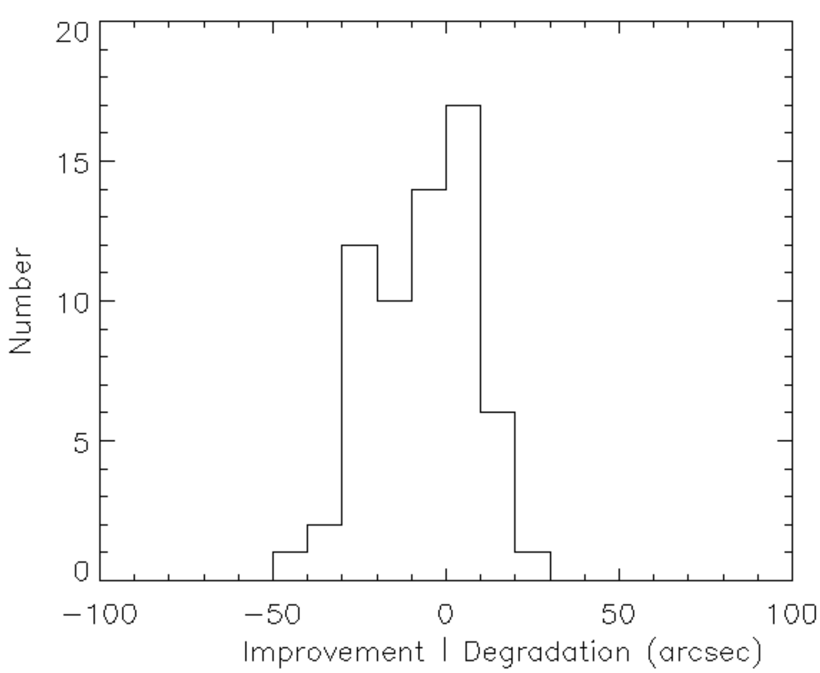

Figure 6. Histogram of position improvements from the Moretti et al. sample. Negative values are an improvement, positive values are a degradation.

The detailed comparison is shown in Figure 6.

6. Caveat Emptor

BAT imaging is highly sensitive to the spacecraft attitude solution. Special care must be taken to exclude and/or correct data for episodes of poor attitude determination. At the crudest level, one must verify that the spacecraft is:

- settled, and
- not in safe hold mode

Users should also check that the spacecraft star tracker status is OK and that the attitude determination error is small. This can be done with the following filter file expression:

```
    (SAC_MODESTAT / 32) % 2 == 1 && SAC_ADERR < 0.2
```

There is some evidence that the spacecraft can report a good attitude solution when in fact it is poor. Example: obsid 130679. In this case, the star tracker reported "OK," but there was in fact a ~3 degree roll error, which caused a significant shift of known bright sources. It is not clear how to address this kind of problem. The star tracker "loss function" --- which is a measure of attitude determination error --- was large during that observation. An analysis of many data sets suggests a threshold of

```
    (STAST_LOSSFCN < 1E-9)
```

may successfully used to reduce these episodes (at the expense of excluding about 1%-2% of the data). However, this filter has not been proved to be correct.

7. Expected Updates

The instrument alignment and aperture pattern are not expected to change appreciably during the mission. However, refined analysis techniques and/or approaches may require new calibration files.

8. Version History

8.1. Update 13 Sep 2007

```
Update 24 Sep 2007
 * New TELDEF files

   BAT instrument TELDEF alignment files have been updated to
account
   for changes in the star tracker alignment (the effective
spacecraft
   boresight).  These changes were implemented by the flight
   operations team in attempts to recover from the August 2007
   safe-hold event.  As a part of this update, all star tracker
   alignment updates have been accounted for, even ones early in
the
   mission (December 2004).  Here is the summary of changes:

       swb20021001v002.teldef PRE-LAUNCH (no change)
       swb20041120v001.teldef OBSOLETED
       swb20041120v002.teldef NEW FILE (represents post-launch
defaults)
       swb20041209v001.teldef NEW FILE
       swb20041213v001.teldef NEW FILE
       swb20041215v001.teldef NEW FILE (represents nominal
2004-2007 default)
       swb20070828v001.teldef NEW FILE (first change
post-safe-hold)
       swb20070904v001.teldef NEW FILE
       swb20070911v001.teldef NEW FILE
```

8.2. Update 07 Apr 2006

```
 * swbdistort20041120v001.fits VERSION 1

   This is a new calibration type.  The distortion map provides a
   measure of the image distortion (i.e. "plate scale" shifts), as
a
   function of position in the BAT field of view.

   The two images are the non-linear distortion of the BAT "plate
   scale" as a function of position in the sky image.  The values
are
   offsets in tangent plane coordinates (IMX,IMY), and therefore
```

```
   unitless.  The first plane of the image cube is the IMX offset,
and
   the second plane is the IMY offset.  The sense of the offset is
   (TRUE-APPARENT), i.e. for a measured position in tangent plane
   coordinates, the offset values should be *added* to arrive at
the
   true position in tangent plane coordinates.  The images are
   low-resolution versions of the BAT field of view in instrumental
   sky coordinates, and are meant to be interpolated to the desired
   sampling.  The WCS keywords describe the image coordinate
systems.

   This file applies to all observation times.  Image distortion
   corrections will be applied in a forthcoming version of the BAT
   science software.
```

8.3. Update 08 Sep 2005

```
 * swbaperflux20041120v001.fits VERSION 1  (NEW FILE)

   This new file is a slightly trimmed aperture map, optimized for
   reproducing the fluxes of cosmic sources.  Because of irregular
and
   unknown passive materials which intrude into the edges of the
field
   of view, the fluxes from the "full" aperture map (swbaperture*)
   will sometimes be degraded, especially if the source is far off
   axis.  This map should reduce the degradation significantly, and
is
   recommended to be used in place of the swbaperture* file.  It
has
   the keyword value APERTYPE = 'FLUX'

 * swbaperedge20041120v001.fits VERSION 1  (NEW FILE)

   This new file shows the trimmed regions that were used to reduce
   the swbaperture* file to the swbaperflux* file.  When used with
the
   batmaskwtimg task, this aperture map shows which portions of the
   array will be illuminated by irregular passive materials, and
   should thus be masked out for bright sources.  The file has the
   keyword value APERTYPE = 'MASK_EDGES'
```

```
 * swbaperture20041120v002.fits VERSION 2

   This new version of the full aperture map is the same as version
1,
   except that it has more pad cells around the edges of the map.
The
   APERTYPE = 'DETECTION' keyword is also present.  The BAT team
now
   considers this map to *not* be optimal for most BAT analysis
work,
   because of the presence of irregular passive materials which
   intrude into the edges of the field of view.  Use swbaperflux*
   instead.

 * swbaperture20030101v003.fits VERSION 3

   This version is the same as version 2, with the addition of the
   APERTYPE = 'DETECTION' keyword (see above).
```

8.4. Updated 24 Dec 2004

```
  * swbaperture20041120v001.fits

     Revised content based on in-flight calibration of the BAT
     boresight.  Contains revised focal length and mask shift
values.
     Validity date: post launch
     [previous file is still valid before launch]

  * swb20041120v001.teldef

     Revised content based on in-flight calibration of the BAT
     boresight.  Contains new misalignment matrix.
     Validity date: post launch
     [previous file is still valid before launch]
```

8.5. Updated 19 Dec 2004

```
 * swb20020101v002.teldef
```

```
     New version, now in accord with HEASARC format
recommendations;
     units of DETX/Y changed to "pixel" (NOTE: no software uses the
     units, so this is for information only)

 * swbaperture20030101v002.fits

     New versions, now in accord with HEASARC format
recommendations.
     Actual contents unchanged from versions 1.
```

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