THE 70 MONTH SWIFT-BAT ALL-SKY HARD X-RAY SURVEY

W. H. Baumgartner1,2,3, J. Tueller1, C. B. Markwardt4, G. K. Skinner1,3,4,5, S. Barthelmy1, R. F. Mushotzky4, P. A. Evans6, and N. Gehrels1

1 NASA/Goddard Space Flight Center, Astrophysics Science Division, Greenbelt, MD 20771, USA; whbaumga@alum.mit.edu
2 Joint Center for Astrophysics, University of Maryland Baltimore County, Baltimore, MD 21250, USA
3 CRESST/Center for Research and Exploration in Space Science and Technology, 10211 Winchester Circle, Suite 500, Columbia, MD 21044, USA
4 Department of Astronomy, University of Maryland, College Park, MD 20742, USA
5 Max-Planck Institut für Extraterrestrische Physik, D-85748 Garching, Germany
6 X-Ray and Observational Astronomy Group/Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK

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ABSTRACT

We present the catalog of sources detected in 70 months of observations with the Burst Alert Telescope (BAT) hard X-ray detector on the Swift gamma-ray burst observatory. The Swift-BAT 70 month survey has detected 1171 hard X-ray sources (more than twice as many sources as the previous 22 month survey) in the 14–195 keV band down to a significance level of 4.8σ, associated with 1210 counterparts. The 70 month Swift-BAT survey is the most sensitive and uniform hard X-ray all-sky survey and reaches a flux level of 1.03 × 10−11 erg s−1 cm−2 over 50% of the sky and 1.34 × 10−11 erg s−1 cm−2 over 90% of the sky. The majority of new sources in the 70 month survey continue to be active galactic nuclei, with over 700 in the catalog. As part of this new edition of the Swift-BAT catalog, we also make available eight-channel spectra and monthly sampled light curves for each object detected in the survey in the online journal and at the Swift-BAT 70 month Web site.

Key words: catalogs – surveys – X-rays: general

Online-only material: color figures, figure sets, machine-readable table, supplemental data files

1. INTRODUCTION

The Swift gamma-ray burst (GRB) observatory (Gehrels et al. 2004) was launched in 2004 November, and has been continually observing the hard X-ray (14–195 keV) sky ever since with the Burst Alert Telescope (BAT). We have previously published BAT survey catalogs covering the first 3 months of data (Markwardt et al. 2005), active galactic nuclei (AGNs) detected in the first 9 months of data (Tueller et al. 2008), and a complete catalog of sources detected in the first 22 months of data (Tueller et al. 2010). This paper extends this work to include all sources detected in the first 70 months of data between 2004 December and 2010 September.

The main advances of the BAT 70 month survey compared to previous Swift-BAT surveys include better sensitivity resulting from a complete reprocessing of the data with an improved data reduction pipeline, the publication of eight-channel spectra, light curves sampled every month throughout the mission, and a lower flux threshold resulting from more integration time by a factor of nearly three.

Hard X-ray source catalogs have also been published based on observations from the INTEGRAL satellite (Bird et al. 2010; Krivonos et al. 2010) and independent analyses of Swift-BAT data by the Palermo group (Cusumano et al. 2010a, 2010b) and by Ajello et al. (2012), Burlon et al. (2011), and Voss & Ajello (2010). The INTEGRAL-based surveys benefit from the somewhat better angular resolution of the IBIS instrument (~12 arcmin versus 19.5 arcmin FWHM for BAT); however, the much narrower field of view (FOV) of IBIS coupled with their observing strategy limits the uniformity of the IBIS sky coverage. This leads to lower sensitivity than BAT surveys over much of the sky away from the galactic plane. In the BAT surveys, the exposure is not biased toward the galactic plane, which leads to deeper and more uniform coverage of evenly distributed objects like AGNs.

The Swift-BAT 70 month survey has paid special attention to compiling a uniform catalog by using a well-defined significance threshold and energy band for inclusion of sources into the catalog. Particular attention has been paid to the identification of sources, for which examination of 3–10 keV X-ray data is crucial. The BAT survey catalogs of Cusumano et al. (2010a, 2010b) often base their counterpart identification on nearby ROSAT sources; Tueller et al. (2010) have shown that the soft X-ray (0.1–2 keV) ROSAT fluxes are not well correlated with the BAT fluxes and could lead to incorrect counterpart associations, especially in the galactic plane. The BAT catalogs of Ajello et al. (2012), Burlon et al. (2011), and Voss & Ajello (2010) often use the counterpart associations of Cusumano et al. (2010b), and utilize only part (15–55 keV) of the full BAT energy band (14–195 keV).

Section 3 describes the data reduction and analysis techniques used in the 70 month BAT survey, concentrating on the improvements made in the data reduction pipeline. Section 4 presents the 70 month catalog of detected sources, spectra, and light curves, and a characterization of the properties of the survey.

2. THE SWIFT MISSION AND THE BAT INSTRUMENT

The BAT on the Swift GRB observatory is a large, coded-mask telescope optimized to detect transient GRBs and is designed with a very wide FOV of ~60° × 100°. Swift’s general observation strategy is to observe pre-planned targets with the narrow FOV X-ray telescope (XRT; which is co-aligned with BAT) until a new GRB is discovered by BAT, at which time Swift automatically slews to the new GRB to follow up with the narrow field instruments for a couple of days until the X-ray afterglow is below the XRT detection limit. This observation strategy is also very well suited for conducting an all-sky survey with the BAT.

The Swift-BAT survey’s most important feature in comparison to the similar INTEGRAL survey (Bird et al. 2010; Krivonos et al.
is its uniform sky coverage. The very wide, instantaneous FOV (\(\sim 1/6\) of the entire sky at 5% partial coding) allows coverage of a relatively large fraction of the sky with each pointing. The effectively random pointing plan caused by GRB observations and follow-up enables coverage of all parts of the sky. The combination of these two properties results in very uniform coverage of the entire sky.

Figure 1 illustrates the sky coverage in the 70 month survey. The center panel is an all-sky exposure map in galactic coordinates. Swift’s pointing constraints (primarily the Sun and Moon constraints) lead to areas of highest exposure at the ecliptic poles. The first panel in Figure 1 shows the distribution of exposure times across the sky, the second panel shows an all-sky exposure map in a galactic projection (with the gray scale indicating megaseconds of exposure), and the right panel shows the fraction of sky covered as a function of exposure time. The areas of highest exposure in the all-sky map are near the ecliptic poles because of Swift’s Sun and Moon avoidance constraints.

#### Table 1

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Energy range               | 14–195 keV                                 |
| Field of view              | \(\sim 85\times 120^\circ\) 0% partial coding |
|                           | 2.29 sr 5% partial coding                  |
|                           | 1.18 sr 50% partial coding                 |
|                           | 0.34 sr 95% partial coding                 |
| Point-spread function      | 195 Mosaic sky maps                         |
|                           | 77’ in center of snapshot FOV              |
|                           | 14’ at corners of snapshot FOV             |
| Detector area              | 5243 cm\(^2\) 32,768 CdZnTe detectors, 4 mm \(\times\) 4 mm \(\times\) 2 mm |
| Aperture                   | 50% open Coded mask, random pattern        |
| Coded mask                 | \(\sim 52,000\) tiles 5 mm \(\times\) 5 mm \(\times\) 1 mm Pb |
| Pointing constraints       | >45’ Sun                                    |
|                           | >30’ Earth limb                            |
|                           | >20’ Moon                                   |

#### Table 2

| Band | Low (keV) | High (keV) | Crab Rate\(^a\) | Crab Error\(^b\) | Crab Flux\(^c\) | Crab Weights\(^d\) |
|------|-----------|------------|-----------------|-----------------|-----------------|-------------------|
| 1    | 14        | 20         | 101.7           | 2.0             | 3.81            | 27.000            |
| 2    | 20        | 24         | 57.0            | 1.3             | 1.87            | 35.260            |
| 3    | 24        | 35         | 100.0           | 2.2             | 3.71            | 22.700            |
| 4    | 35        | 50         | 60.1            | 1.5             | 3.32            | 29.444            |
| 5    | 50        | 75         | 48.7            | 1.5             | 3.56            | 21.272            |
| 6    | 75        | 100        | 17.9            | 1.1             | 2.40            | 16.062            |
| 7    | 100       | 150        | 9.3             | 1.0             | 3.21            | 8.449             |
| 8    | 150       | 195        | 1.4             | 0.7             | 1.98            | 2.630             |

Notes.

\(^a\) 10\(^{-4}\) counts s\(^{-1}\) detector\(^{-1}\).
\(^b\) 10\(^{-6}\) counts s\(^{-1}\) detector\(^{-1}\). Computed from the rms noise in a large annulus around the Crab (see Section 4.3).
\(^c\) Calculated from Equation (5), in units of (10\(^{-9}\) erg s\(^{-1}\) cm\(^{-2}\)).
\(^d\) These weights are used when combining the eight individual band maps into the total band map for source detection purposes. See Section 3.5.

(a single Swift pointing of \(\sim 20\) minutes) are extracted in the eight bands listed in Table 2 and combined into all-sky mosaic images. The eight-band mosaics are combined into a total band map and a blind search for sources is done by finding all pixels above the 4.8\(\sigma\) detection threshold that are higher than each of their immediately surrounding neighbors. Then we use the rough positions of these blind sources as inputs to a stage where we more carefully fit for the BAT positions of these sources. After that, we identify counterparts to the blind sources by searching archival X-ray images from high resolution instruments like Swift-XRT, Chandra, and XMM-Newton. This step allows for the identification of previously known X-ray sources as well as uncataloged X-ray point sources that can be checked against databases such as SIMBAD and NED for associations with objects in other wavebands (such as galaxies in the Two Micron All Sky Survey (2MASS) extended source catalog). Finally, we associate the blind sources with counterparts by searching the counterparts list for objects within a fixed match radius of each blind source.

### 3. Procedure

The data reduction and analysis for the BAT 70 month survey are based on the procedures used in the BAT 22 month survey. The complete analysis pipeline is described in the BAT 22 month paper (Tueller et al. 2010).

The data analysis and catalog generation process can be briefly summarized as follows. The data from each snapshot
These changes have necessitated a complete reprocessing of all the data from the BAT survey to ensure uniformity and homogeneity. This reprocessing is different from our past procedure of processing new data periodically (on a several month timescale) and incorporating improvements to the data reduction pipeline before each processing run of new data. The current reprocessing of all the data for the 70 month survey should lead to more homogeneous results and a more uniform survey than the incremental processing used for preparing previous catalogs.

We have also introduced minor changes in the data analysis and catalog generation procedures. These include the handling of confused sources, the fitting of spectra and the calculation of the flux, the determination of the match radius for finding counterparts, the computation of the spectral index instead of the flux, the determining of the match radius for finding confused sources, the fitting of spectra and the calculation of the flux, and the handling of photoelectric observations.

3.2. Gain Correction

Analysis of the BAT calibration spectra over the course of the Swift mission shows that the detector energy channel containing the 59.5 keV peak from the $^{241}$Am tagged source has gradually shifted as a function of time (see Figure 2). This shift of up to about 3% in the BAT energy scale is due to a small, continual decrease in the gains of the individual CZT detectors. The data processing pipeline used in the analysis of 9 month and 22 month versions of the Swift-BAT survey catalog did not take this gain variation into account, leading to slightly low energies being assigned to the detected X-rays.

For most detectors, this led to a small change in the fluxes detected in each of the eight spectral channels—individual photons had too low of an energy assigned to them, and counts shifted to lower channels or below the low-energy threshold. Variations in gain among detectors also cause imaging noise as counts from different energy bands fall into and out of the expected mask shadow in the detector plane.

In order to correct for the gain decreases in BAT, we fit the position of the peak channel of the 59.5 keV calibration line as a function of time throughout the mission. We then use the peak channel position to determine a gain correction factor for each detector as a function of time. This gain correction factor is then used to correct the bin edge location in the channel space of the BAT energy bands.

The physical origins of the gain shifts in CZT are not fully known. A leading hypothesis is that over time, radiation damage creates more charge traps in the CZT, reducing the charge collection efficiency and hence reducing the gain. There is also some indication that pixels with the best charge collection properties at launch suffered the largest gain decreases over time, while pixels with lower charge collection efficiencies (and $\mu\tau$ products) suffer less from gain decreases. The differing susceptibility of each pixel to gain shifts over time is what causes the broadening in the pixel gain distribution.

We correct for these gain shifts on a pixel-by-pixel basis using energy calibration data from the tagged source as described above. The spectra in this paper are taken from eight broad energy bands, and so are not expected to suffer noticeably from response broadening due to differing reductions in CZT gain.

3.3. Cleaning of Bright Sources

During the course of the BAT survey data processing, sky maps are generated from each spacecraft pointing and then combined into mosaicked maps. In order to reduce the systematic noise present in the maps from the sidelobes of strong sources, the analysis “cleans” bright sources found in the individual snapshot images. This means that if a source is detected in a snapshot image with a significance greater than 6$\sigma$, we measure its flux and subtract the contribution of the source with the fitted strength. After all of the bright sources above the cleaning threshold are removed in this way, the cleaned maps are combined with the mosaicked maps and source detection is performed to locate sources with lower significance.

The data processing pipeline for previous versions of the BAT survey catalog used a cleaning threshold of 9$\sigma$ in the individual snapshot images. For the 70 month survey catalog, we lowered the threshold to 6$\sigma$ in order to further reduce the systematic noise in the mosaicked maps due to strong sources. In addition, we have designated 100 objects as sources that are cleaned in every snapshot image, regardless of detected significance. These are primarily the brightest sources in the survey, usually galactic and variable. These sources are always cleaned even if they are below the 6$\sigma$ threshold for cleaning in a single snapshot image. This allows us to remove systematic noise caused by these strong sources from the mosaicked maps without becoming vulnerable to unnecessary cleaning of noise peaks as a result of a lower snapshot cleaning threshold.

3.4. Pixelization in Mosaicked Sky Maps

The individual snapshot sky maps are combined into the mosaicked map by interpolating the pixel values from the snapshot grid onto the mosaic grid. In previous versions of the data processing, the mosaic pixel grid pitch was 5.0 arcmin (the point-spread function (PSF) in the BAT mosaicked images can be described by a Gaussian with 19.5 arcmin FWHM). For the 70 month survey we have chosen to use a smaller mosaic grid with a pixel pitch of 2.8 arcmin. This change to smaller

![Figure 2. BAT detector gain as a function of time throughout the first 48 months of the Swift mission. The y-axis is the offset (in keV) between the location of the measured and nominal 59.5 keV line from the $^{241}$Am calibration source. The x-axis is broken down into successive three-month periods in which a black point is plotted for each of the 32,768 detector elements in the BAT array. The red crosses are the three-month averages (and rms spread) for all the detectors in the entire BAT array. The BAT 70 month survey has gain values for months 0–48; for survey data acquired after month 48, we keep the detector gains fixed at their 48 month values. (A color version of this figure is available in the online journal.)](image)
mosaic pixels allows a more accurate determination of source positions and fluxes by reducing the effects of interpolation error when adding the individual snapshot images to the mosaicked images. The choice of a 2.8 arcmin mosaic pixel size results from a compromise between high precision in the mosaicked images and reasonable computation times for the data processing.

### 3.5. Crab Weighting

In previous iterations of the Swift-BAT survey, the mosaicked total-band map (14–195 keV) used for detecting new sources was produced by simply summing together the individual maps from the eight energy bands of the survey. This is equivalent to performing a weighted sum across the eight energies, with each band having a weight of unity.

In order to improve the sensitivity of the source detection stage in the 70 month survey to objects with AGN-like spectra, we have adopted new weights derived from the measured Crab count rates in the eight bands. This has the effect of enhancing detection for sources with a Crab-like power-law spectrum. Since most AGNs have power-law-like spectra with spectral indices of \( \sim 2 \) (close to the Crab’s spectral index of 2.15; see Equation (5)), we expect this Crab-weighting to improve our detection sensitivity for AGNs.

In Crab units, the count rate and noise rate of an individual pixel in the combined map can be represented as \( F_i/K_i \) and \( n_i/K_i \) where \( F_i \) is the measured count rate in the energy band \( i \), \( K_i \) is the measured Crab rate, and \( n_i \) is the measured noise rate. Combining these individual band measurements in a weighted mean (and dropping the subscripts) yields

\[
F_{cw} = \frac{1}{\sum (K/n)^2} \sum \frac{F/K}{(n/K)^2},
\]

where \( F_{cw} \) is the Crab-weighted total count rate in counts s\(^{-1}\) detector\(^{-1}\). This is equivalent to

\[
F_{cw} = \sum \frac{F (K/n_i^2)}{\sum (K/n)^2}.
\]

If we express the weighted sum more simply as

\[
F_{cw} = \sum_{i=1}^{8} W_i F_i,
\]

then the weights \( W_i \) can be constructed with the following formula:

\[
W_i = \frac{K_i}{n_i^2 \sum (K_i/n_i)^2}.
\]

Figure 3 shows the sensitivity of the source detection process to the spectral slope used to compute the weights for combining the individual energy bands. The values for the measured count rate of the Crab in the eight energy bands, the noise, and the derived values of the weights can be found in Table 2.

### 4. THE SWIFT-BAT 70 MONTH CATALOG

Table 3 lists all the sources detected above the 4.8\( \sigma \) level in a blind search of the 70 month Swift-BAT survey maps. The first column is the source number in the 70 month catalog. The second column is the BAT name, constructed from the BAT source position given in columns 3 and 4. In cases where the source has been previously published with a BAT name corresponding to a slightly different location (e.g., a source position from a previous BAT catalog with less exposure), we have used the first published name but have given the 70 month BAT coordinates in columns 3 and 4. If there is more than one X-ray counterpart to a single BAT source, we have repeated the BAT name with an “A” or “B” suffix and used the same BAT coordinates for each of the counterparts. The fifth column is the significance of the blind BAT source detection. The significance was calculated by taking the flux at the highest pixel discovered in the blind search in the total-band mosaic and dividing by the local noise as discussed in Section 4.3. Instances where more than one possible counterpart to a single BAT source is found within the match radius of 22 arcmin are indicated with ditto marks in columns 2–5. We use the 4.8\( \sigma \) significance level as the threshold for inclusion in the survey as discussed in Tueller et al. (2010), since we expect one false BAT detection in the entire sky at this significance level.

The sixth column gives the name of the counterpart to the BAT hard X-ray source. These are often well-known X-ray sources, optical galaxies, or 2MASS sources, and are associated with a source detected in the medium-energy X-ray band (3–10 keV) in Swift-XRT, Chandra, or XMM-Newton images. If no counterpart to the BAT source has been identified, we give the BAT name from column 2 as the counterpart name. Counterpart determination is discussed in more detail in Section 4.1. The seventh column gives an alternate name for the counterpart; we list a well-known name or a name from a hard X-ray instrument or high energy detection. The best available coordinates of the counterparts (J2000) are given in the table in columns 8 and 9.

The 10th and 11th columns give the 14–195 keV flux of the BAT source (in units of \( 10^{-12} \) erg s\(^{-1}\) cm\(^{-2}\) and the

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7 [http://swift.gsfc.nasa.gov/docs/swift/results/bs70mon/](http://swift.gsfc.nasa.gov/docs/swift/results/bs70mon/)
Table 3
Catalog of Sources in the 70 Month Swift-BAT Survey

| Num | BAT Name  | R.A. | Decl. | S/N | Counterpart Name | Other Name | Cpt R.A. | Cpt Decl. | Flux^a | Error Range^b | Flip | Chi^2 | Lum^c | As^d | Cl^e | Type |
|-----|-----------|------|-------|-----|------------------|------------|----------|-----------|--------|--------------|------|-------|-------|------|------|------|
| 1   | SWIFT J0001.0-0708 | 0.261 | -7.123 | 6.10 | 2MASX J00004876-0709117 |           | 0.2032   | -7.1532  | 13.03  | 9.05–17.56   | 2.17 | 1.75–2.69 | 0.60  | 2    | Galaxy |
| 2   | SWIFT J0001.6-7701 | 0.326 | -77.001 | 5.41 | Fairall J203     |           | 0.4419   | -76.9540| 10.10  | 6.61–14.08   | 2.02 | 1.54–2.60 | 0.70  | 0.0584 | 43.92 | 4    | Sy1    |
| 3   | SWIFT J0002.5+0323 | 0.664 | 3.332  | 5.10 | NGC 7811         |           | 0.6103   | 3.3519  | 11.69  | 7.36–16.64   | 1.82 | 1.31–2.39 | 0.50  | 0.0255 | 43.24 | 4    | Sy1.5  |
| 4   | SWIFT J0003.3+2737 | 0.862 | 27.676 | 5.03 | 2MASX J00032742+2739173 |       | 0.8643   | 27.6548| 13.00  | 8.76–17.70   | 1.66 | 1.25–2.12 | 1.00  | ?     | 2      | Galaxy |
| 5   | SWIFT J0005.0+7021 | 1.011 | 70.327 | 7.20 | 2MASX J00040192+7019185 | IGR J00040+7020 | 1.0082   | 70.3217| 12.67  | 9.38–16.33   | 2.19 | 1.83–2.61 | 0.70  | 0.0960 | 44.47 | 5    | Sy2    |
| 6   | SWIFT J0006.2+2012 | 1.580 | 20.178 | 10.04 | Mrk 335         |           | 1.5813   | 20.2029| 18.43  | 14.79–22.42  | 2.32 | 2.03–2.65 | 0.30  | 0.0258 | 43.45 | 4    | Sy1.2  |
| 7   | SWIFT J0009.4–0037 | 2.316 | -0.575 | 4.99 | 2MASX J00091156-0036551 |       | 2.2982   | -0.6152| 9.26   | 5.31–13.99   | 2.14 | 1.52–2.97 | 0.40  | 0.0733 | 44.08 | 5    | Sy2    |
| 8   | SWIFT J0107.0+1057 | 2.612 | 10.953 | 13.35 | Mrk 1501        |           | 2.6292   | 10.9749| 31.37  | 26.89–36.08  | 1.87 | 1.68–2.07 | 0.90  | 0.0893 | 44.80 | 4    | Sy1.2  |
| 9   | SWIFT J0107.1+8134 | 4.268 | 81.567 | 6.58 | [HB89] 0014+813 | PKS 0018-19 | 4.2853   | 81.5856| 10.12  | 7.16–13.58   | 2.53 | 2.04–3.14 | 1.60  | 3.3660 | 48.01 | 8    | QSO/FSRQ |
| 10  | SWIFT J0212.2–1909 | 5.305 | -19.151 | 8.54 | 2MASX J00210753-1910056 |       | 5.2814   | -19.1682| 17.28  | 13.33–21.64  | 2.06 | 1.76–2.41 | 0.80  | 0.0956 | 44.60 | 5    | Sy2    |

Notes.

# If a BAT name exists in the 22 month catalog (Tueller et al. 2008), then that name is used. If there is no 22 month BAT name, then the BAT name listed here is the name that was used to request XRT follow-up observations (and used in the HEASARC archive). When no previous BAT name for this source exists, we list here a BAT name derived from the BAT position in this catalog.

# The BAT source positions listed here are all uniformly generated from the fit BAT positions of the sources in the 70 month data, and are J2000 coordinates.

# The counterpart position is the most accurate known position of the object in the “Name” column in J2000 coordinates, and is usually taken from NED or SIMBAD. If no counterpart is known, the fit BAT position is listed.

# The flux is extracted from the BAT maps at the position listed for the counterpart, is in units of \(10^{-12}\text{erg s}^{-1}\text{cm}^{-2}\), and is computed for the 14–195 keV band.

# The error range is the 90% confidence interval.

# The contaminated column indicates what portion of the BAT flux at the counterpart position is contributed by other nearby sources.

# The spectral index is computed from a power-law fit to the eight-band BAT data.

# The redshifts are taken from the online databases NED and SIMBAD or in a few cases from our own analysis of the optical data. A blank indicates that the object is Galactic, and a ? indicates that the object has an unknown redshift.

# The luminosity is computed from the flux and redshift in this table, with units of \(\log(\text{erg s}^{-1})\) in the 14–195 keV band.

# Association strength.

# Source class.

References. Bikmaev et al. 2008, 2006; Bodaghee et al. 2006, 2007; Burenin et al. 2008; Butler et al. 2009; Chakrabarty et al. 2002; Coe et al. 1994; Homer et al. 2002; Israel et al. 2001; Juett & Chakrabarty 2005; Markwardt et al. 2005; Masetti et al. 2008, 2009; Rodriguez et al. 2009; Tomsick et al. 2008; Tueller et al. 2008; Walter et al. 2006; Wilson et al. 2003; Landi et al. 2011; Hogg et al. 2011; Parisi et al. 2009, 2012; Landi et al. 2007; Ciroi et al. 2009; Kniazev et al. 2010.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
90% confidence interval. The BAT flux for each counterpart is extracted from the hard X-ray map at the location of the counterpart given in columns 8 and 9. The flux determination method uses a power-law spectral fit with the flux measurements in each of the eight energy bands, and is described in Section 4.3.

The 12th column indicates whether there is contamination of the flux measurement from nearby sources. This can be the result of source confusion (two BAT sources close enough together to be unresolved, or two viable counterparts within the same BAT mosaic pixel), or from the presence of a strong nearby source. The number given is the contamination fraction, or the fraction of the measured flux at the counterpart position contributed by other sources. Contamination fractions are given for all sources with a contamination level greater than 2%. The treatment of confused sources and of contaminated flux measurements is described in more detail in Section 4.4.

When a source has an entry in column 12 and is considered to be confused, the counterpart flux listed in column 10 is an estimate from a simultaneous fit of all the counterparts in the region to the BAT map. In these cases, the error on the flux is not well defined and column 11 is left blank (see Section 4.3). The 13th and 14th columns list the source spectral index and error in the BAT band as described in Section 4.3. The 15th column lists the reduced $\chi^2$ value from a spectral fit to a power-law model (see Section 4.3).

The 16th and 17th columns give the redshift and BAT luminosity of the counterpart if it is associated with a galaxy or AGN. The source luminosity (with units log[erg s$^{-1}$]) in the 14–195 keV band is computed using the redshift and flux listed in the table and a cosmology where $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.30$, and $\Omega_k = 0.70$.

The 18th column can contain a flag indicating the strength of the association between the BAT source and the listed counterpart (see Section 4.1.1).

The 19th column gives an integer source class that we have found useful for selecting particular classes of objects (e.g., AGNs, HMXBs). The source classes are listed in Table 4.

The 20th column lists a source type in the form of a short description of the counterpart.

4.1. Counterparts

As mentioned in Section 3 and described in more detail in Tueller et al. (2010), counterparts to the BAT sources were identified by examining archival X-ray observations from Swift-XRT, Chandra, XMM-Newton, Suzaku, and ASCA. All point sources near the blind BAT source position (within $\sim 15$ arcmin) were checked to see whether an extrapolation of the X-ray spectrum fit into the BAT band would be consistent with the measured BAT flux. Any such X-ray sources with an extrapolated flux above the BAT detection threshold were checked against SIMBAD and NED to determine a source name and type, and saved to a file containing all discovered counterparts.

Where there were no archival X-ray observations covering the BAT source, we submitted the coordinates to the Swift-XRT for a 10 ks X-ray follow-up observation. In cases where we did not yet have X-ray observations of the BAT source from the X-ray archives or from Swift-XRT, a best guess was made as to the counterpart by checking for likely sources (e.g., strong, nearby Seyfert galaxies) in NED and SIMBAD. These cases are indicated in Table 3 using the association strength flag in column 18 as described in Section 4.1.1.

| Class       | Source Type                  | Number |
|-------------|------------------------------|--------|
| 0           | Unknown$^a$                  | 65     |
| 1           | Galactic$^b$                 | 23     |
| 2           | Galaxy$^c$                   | 111    |
| 3           | Galaxy Cluster               | 19     |
| 4           | Seyfert I (Sy 1.0–1.5)       | 292    |
| 5           | Seyfert II (Sy 1.7–2.0)      | 261    |
| 6           | Other AGN                    | 23     |
| 7           | Blazar/BL Lac object         | 49     |
| 8           | QSO$^d$                      | 86     |
| 9           | Cataclysmic variable star (CV)| 55    |
| 10          | Pulsar                       | 20     |
| 11          | Supernova remnant (SNR)      | 6      |
| 12          | Star                         | 14     |
| 13          | High mass X-ray binary (HMXB)| 85    |
| 14          | Low mass X-ray binary (LMXB)  | 84    |
| 15          | Other X-ray binary (XRB)     | 17     |
|             | Total                        | 1210   |

Notes.

$^a$ Sources listed with the type unknown either do not have any known counterpart, or are associated with sources of unknown physical type.

$^b$ Sources classified only as “Galactic” are so assigned because of observed transient behavior in the X-ray band along with insufficient evidence to place them in another class.

$^c$ Sources in the “Galaxy” class are seen as extended in optical or near-IR imagery, but do not have firm evidence (such as an optical spectrum) from other wavebands confirming whether they harbor an AGN.

$^d$ AGNs with BAT luminosities greater than $10^{45}$ erg s$^{-1}$ or listed in NED as radio galaxies are classified as QSO.

There are a few complications to this procedure. The blind source detection technique used on the BAT mosaics (see Tueller et al. 2010) does not do a good job of automatically discovering weaker BAT sources close to very strong sources. To guard against this case we checked the BAT mosaics by eye to ensure that all sources detected by BAT are listed in Table 3.

Source detection is especially difficult in the crowded galactic center region. Figure 4 illustrates this problem with the BAT map of the galactic center region. The separation between sources in this crowded region can be on the order of the 19.5 arcmin (FWHM) PSF of the BAT survey. Given the difficulty with source detection and confusion in the galactic center region, we have chosen by hand a reasonable set of the brightest counterparts needed to explain the measured BAT emission in this area.

4.1.1. Counterpart Associations

One of the main goals of the BAT 70 month survey is to produce a uniform and well-identified catalog of hard X-ray sources in the sky. In order to achieve this goal we have paid particular attention to the assignment of counterparts to the sources detected by BAT. Instead of just cross-correlating the BAT catalog with catalogs from other telescopes, we have whenever possible checked the archives for X-ray observations of the fields containing BAT sources. We believe that this level of effort is necessary in order to produce the most useful catalog for further studies of hard X-ray sources.

An indication of the strength of the association between the BAT source and the counterpart listed in the main table is listed in column 18. This flag is meant to indicate the result of a check
Figure 4. The galactic center as seen by BAT. The colors of the sources were derived from the eight-band mosaics: the lowest two bands (14–24 keV) are combined to give a red value for each pixel, 24–50 keV for green, and 50–150 keV for blue. The colors are then adjusted to the Crab spectrum, so that white sources have a Crab-like spectrum, red sources are softer, and blue sources are harder. The grid is in galactic coordinates. The circular regions are centered on the counterparts listed in Table 3 and have a 10 arcmin radius. The PSF of BAT in the mosaicked maps is 19.5 arcmin.

(A color version of this figure is available in the online journal.)

Table 5
Counterpart Association Strengths

| Flag   | Number | %    | Meaning                                      |
|--------|--------|------|----------------------------------------------|
| (Blank)| 1017   | 84.2 | Confirmed with X-ray imaging                 |
| 1      | 36     | 3.0  | Old association held over from previous catalog |
| 2      | 5      | 0.4  | No good hard X-ray source; soft X-ray source |
| 3      | 4      | 0.3  | No X-ray source; source from another waveband |
| 4      | 133    | 11.0 | Unchecked or unavailable X-ray image; educated guess |
| 5      | 2      | 0.2  | No X-ray source; BAT source on Galactic plane |
| 6      | 10     | 0.8  | No X-ray source; BAT source off plane         |
| 7      | 3      | 0.2  | No association                               |

The strongest association is indicated by a value of 0 (blank in the printed table) in the association strength column. These sources have been observed in the medium-energy X-ray band (3–10 keV), and images of the fields have been checked for possible counterparts to the BAT hard X-ray source. Any sources found are checked to see whether their X-ray spectrum extrapolated into the BAT band yields a flux value above the BAT survey threshold. This is often indicated by the presence of the source in the medium-energy X-ray band since most sources found in the total X-ray band (0.5–10 keV) are soft and do not have BAT counterparts. Over 80% of the counterparts to sources in the BAT 70 month survey have been verified with X-ray observations; although 100% of the BAT sources have archival X-ray observations, 20% of the sources have X-ray data that remain to be analyzed.

A value of 1 indicates that the counterpart association has been held over from a previous catalog, but may not have been explicitly checked with X-ray archival data. These are usually very bright or galactic sources.

A value of 2 in the association strength column indicates an intermediate-level association. A value of 2 means that an examination of an X-ray image found a plausible soft (1–10 keV) source, but that the source is weak or nonexistent in the hard band (4–10 keV). A value of 3 indicates that the evidence for the counterpart association comes from another waveband, such as an optical or radio QSO catalog.

A value of 4 in the association strength column means that this source has archival X-ray data but it has not yet been checked to verify the association listed in the catalog. The listed association is based on the presence of a nearby object in the SIMBAD or NED databases likely to be the counterpart to the BAT source. Such sources are usually bright Seyfert galaxies or QSOs, or bright galactic sources. Past experience with previous BAT catalogs has shown that counterpart associations made in
this way and later verified with X-ray observations are correct greater than 95% of the time.

A value of 5 or 6 in the association strength column indicates that the field has been observed in the X-ray band but that no counterpart was found. This usually indicates that the BAT source is transient and not detected in the X-ray observation. Sources on the galactic plane are indicated with a 5, and sources greater than 10° from the galactic plane are indicated with a 6.

A value of 7 in the association strength column means that the source has no archival data for observations in other wavebands and that no suitable counterpart has been found.

4.2. Source Types and Distribution

Figure 5 shows the distribution of sources on the sky, color-coded by source type, with the symbol size proportional to the source flux in the 14–195 keV band. Table 4 gives the distribution of objects according to their source type. Sources classified as “unknown” are those where the physical type of the underlying object (e.g., AGN, CV, XRB) has not yet been ascertained. These sources often have a primary name derived from the BAT position. Some BAT sources of unknown type are associated with named sources discovered by other missions in the X-ray or gamma-ray bands, but are classified as unknown in Table 3 because the physical type of the named source is unknown or because the coordinates of the source are not precise enough to identify an optical counterpart. These sources have been distinguished by being named in the catalog based on the observation in the other waveband. The few sources classified only as “Galactic” generally lie in the plane and have shown some transient behavior that indicates a galactic source, but no other information is available that would allow further classification. Sources labeled “Galaxy” are detected as extended sources in optical or near-IR imaging, but do not yet have spectroscopic evidence of being an AGN.

4.3. BAT Fluxes and Spectra

The fluxes of the counterparts to BAT sources were extracted in the eight BAT bands from the mosaicked maps using the pixel containing the position of the identified counterpart. For sources where a counterpart is not known, we use the fitted BAT position to extract the flux in the eight bands. The errors associated with the flux values were calculated by computing the rms value in the mosaicked maps in an area around each source with a radius of 100 pixels (4.5'). An exclusion zone around the source with a radius of 15 pixels (40.5 arcmin) was applied to the central source and any nearby sources that fell in the background calculation area.

As in Tueller et al. (2010), we fit these eight-channel spectra with a power-law model in order to find the flux of each source. We use a BAT spectral response matrix generated by the BAT software batdrmgen. The BAT response matrix is normalized to yield the correct flux for the Crab, where we take the Crab counts spectrum to be

$$F(E) = 10.17 E^{-2.15} \left( \frac{\text{photons}}{\text{cm}^2 \text{s keV}} \right)$$

which yields a total Crab flux of

$$\text{Crab flux} = \int_{14 \text{ keV}}^{195 \text{ keV}} EF(E) dE = 2.386 \times 10^{-8} \left( \frac{\text{erg}}{\text{cm}^2 \text{s}} \right).$$

The measured values of the Crab count rate in the eight bands of the BAT 70 month survey and the Crab flux values in those bands are given in Table 2.

We use the XSPEC fitting software to fit the eight-channel spectra with the pegpwrlw model (power law with pegged normalization) over the 14–195 keV BAT survey energy range. We list the spectral index and flux determined from the fit in Table 3.

The 90% confidence intervals for the overall flux and the spectral index were found by using the error function in XSPEC and are given in Table 3. For the highest-significance

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8 More information on the software tool batdrmgen used to produce a BAT response matrix can be found in the BAT software manual at: http://heasarc.nasa.gov/docs/swift/analysis/bat_swguide_v6_3.pdf. We used batdrmgen version 3.6 in this work.
Figure 6. BAT spectra of four sources in the 70 month catalog. The line in the plots is a simple power-law fit to the data, with the power-law index given as $\Gamma$ in the legend. (The complete figure set (1210 images) is available in the online journal.)

Figure 7. Light curves of four sources from the 70 month catalog. (The complete figure set (1210 images) is available in the online journal.)

BAT sources (> 100σ), this procedure does not produce a good fit (reduced $\chi^2 \gg 1$). However, this is to be expected from the very high significance of each data point, the coarse energy binning, and because a simple power law is not a good model for the spectra of many galactic objects. We list the reduced $\chi^2$ for each source in Table 3 as an indicator of which sources are not well fit with a power-law model, but leave a more detailed spectral analysis to a later work.

We provide the eight-band BAT spectra for all sources detected in the 70 month survey as fits files on our Web site 7 and in the online journal.

Figure 6 shows the spectra of four representative sources from the BAT 70 month survey.

4.4. Confused Sources

Sources are labeled as confused in our table (i.e., they have a value in the contamination fraction column of Table 3) when the highest pixel associated with the BAT source in the mosaicked maps (the “central pixel” value) has a significant contribution from adjacent sources. This includes the cases when two possible X-ray counterparts lie within a single BAT pixel and when two BAT sources are close enough that each contributes flux at the location of the adjacent source.

Using the positions of the X-ray counterparts as an input catalog, we determined the contamination fraction of each source by using the mosaicked total-band map to simultaneously fit for the intensity of a PSF (a 19.5 arcmin FWHM Gaussian) centered at the location of each source. Using these fit values, we decompose the measured flux at each source location into a contamination rate contributed from nearby sources and a fit rate for the central source. We then compute a contamination fraction:

$$\text{Contamination Fraction} = \frac{\text{Contamination rate}}{\text{Fit rate}}.$$ 

If the source has a contamination fraction greater than 2%, we list the value in Table 3 and consider the source confused.

The fluxes for sources marked as confused were calculated in a slightly different way than for unconfused sources. Instead of using the measured count rate extracted from the map at the counterpart position, we use the decomposed fit rate extracted in each energy band to form the source spectrum from which the flux is calculated. For these sources we do not quote an error on the flux estimate because the errors produced with this fitting technique are not well-behaved. Any source with a contamination fraction greater than 2% can be considered to be detected by BAT, but the quoted flux should be considered an upper limit.

4.5. Light Curves

Another important goal of the 70 month survey is to make available light curves that span the 70 month period of the survey for the sources detected by BAT. In order to achieve this, we have constructed all-sky total-band mosaic images for each month of data in the survey. We extract from the monthly mosaics fluxes for all the sources detected in the full survey and use these to construct monthly sampled light curves that cover the duration of the survey.

Figure 7 shows four representative light curves from the BAT 70 month survey. The fourth panel of the figure shows the light curve of the Crab. The error bars on the data points are constructed from the local noise in the monthly mosaic image and are representative of the statistical error associated with each data point. The five points with very large error bars result from times when the Sun is near the Crab’s position in the sky and Swift is constrained against pointing in that direction, resulting in smaller exposure times and larger error bars.

Wilson-Hodge et al. (2011) have shown that the flux of the Crab in the BAT band is not constant, but shows variations of 10% over timescales on the order of one year. This behavior matches what we see in the BAT light curve of the Crab. As in Wilson-Hodge et al. (2011), we estimate the systematic errors in the BAT light curves to be $\sim 0.75\%$ of the source flux by assuming that the long-term (months-to-years) variations in the
Figure 8. The BAT position error as a function of the BAT detection significance. The angular separation between the counterpart position and the fitted BAT position is used to determine a measured position error for each source. Sources closer than 5° from the galactic plane and galaxy clusters were not included. The measured position error is plotted as a function of BAT detection significance. The dashed line in the plot shows the 91% error radius as a function of BAT source detection significance (see Section 5.1).

Crab light curve are due to real variations in the Crab, and that the shorter term variations around that trend are representative of the systematic error in the measurements.

The light curves for each source detected in the survey can be found at the Swift-BAT Web site and in the online journal. Due to the large size, the sources are presented in six separate packages, each separated in groups of 4 hr of R.A. (00–04, 04–08, 08–12, 12–16, 16–20, and 20–24).

5. SURVEY CHARACTERIZATION

5.1. Source Positional Uncertainty

In order to judge the accuracy of the BAT positions, we plot in Figure 8 the angular separation between the BAT position and the counterpart position against the significance of the BAT source detection. In Figure 8 we also plot a line showing our estimate of the BAT position uncertainty for a given source significance. This estimate for the error radius (in arcminutes) can be represented with the function

\[
\text{BAT error radius (arcmin)} = \sqrt{\left(\frac{28}{(S/N)}\right)^2 + (0.3)^2},
\]

where S/N is the BAT detection significance. This empirical function includes a systematic error of 0.3 arcmin deduced from the position errors of very significant sources. This systematic error is consistent with differential aberration across the very large BAT FOV and with small offsets caused by the slightly energy dependent focal length of BAT. 91% of the BAT sources not on the galactic plane (l > 5°) have counterparts that are within this position error radius.

5.2. Measured and Theoretical Sensitivity and Systematic Errors

In this section we compare the expected errors with the actual measured noise in the final mosaic maps.

5.2.1. Exposure and Noise and Systematic Errors

The observed noise in the 70 month survey can be considered to contain a primary component related to the statistical uncertainty (dominated by the exposure time), and a systematic component caused by things like the incomplete cleaning of bright sources from the maps. Figure 9 shows the exposure-corrected noise map for the 70 month survey. With the statistical component of the noise removed, the systematic noise component can be seen to be concentrated in the center of the galactic plane near the location of many of the brightest sources in the sky. This suggests that the dominant contribution to the systematic noise is from incomplete cleaning of bright sources.

5.2.2. Predicted Noise

From the perspective of pure Poisson counting statistics, the uncertainties are governed primarily by the properties of the coded mask and the background (see Skinner 2008 for details).

Figure 9. Systematic noise map for the BAT 70 month survey in galactic coordinates. The contours are in arbitrary units. The measured noise map was exposure-corrected in order to highlight the systematic error contributions. The highest noise levels (and lowest sensitivity) are in the galactic center area, which contains many bright sources.
The expected $5\sigma$ noise level can be expressed as (adapted from Skinner 2008, Equations (23) and (25)):

$$5\sigma_{\text{Poisson}} = 5 \sqrt{\frac{2b}{\alpha N_{\text{det}} T}}$$

where $b$ is the per-detector rate, including background and point sources in the FOV; $N_{\text{det}}$ is the number of active detectors ($N_{\text{det}} \leq 32,768$); $T$ is the effective on-axis exposure time; and $\alpha$ is a coefficient dependent on the mask pattern and detector pixel size ($\alpha = 0.27$ for BAT).\footnote{In Tueller et al. (2010) a typographical error incorrectly listed $\alpha = 0.733$ for BAT.} The partial coding, $p$, enters the expression through the “effective on-axis exposure” time, $T' = \rho T_o$, where $T_o$ is the actual exposure time. Using the measured and exposure-weighted values for the background in each band and the Crab weights given in Table 2 ($b = 0.246 \text{ counts s}^{-1} \text{ detector}^{-1}$; $N_{\text{det}} = 22,520$ (the exposure-weighted mean number of enabled detectors); and the measured count rate of the Crab from the mosaics\footnote{In Tueller et al. (2010), we used a value for the Crab count rate of $4.59 \times 10^{-2} \text{ counts s}^{-1} \text{ detector}^{-1}$. However, this rate was incorrectly based on data taken from the individual snapshot images instead of from the mosaics.} of $3.86 \times 10^{-2} \text{ counts s}^{-1} \text{ detector}^{-1}$), we find the estimated Poisson $5\sigma$ noise flux level to be

$$f_{5\sigma} = 1.18 \text{ mCrab} \left(\frac{T}{1 \text{ Ms}}\right)^{-1/2}.$$  

The values for $b$ and $N_{\text{det}}$ have been measured in the 70 month survey as opposed to only being estimated in the 22 month survey paper, so we believe we have improved our computation of the expected noise.

Using the median exposure time of 9.45 Ms shown in Figure 1, we use Equation (9) to obtain the expected median value for the $5\sigma$ sensitivity of the 70 month survey of 0.38 mCrab, or $9.2 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ using Equation (6).

### 5.2.3. Measured Noise

The sensitivity of the Swift-BAT survey is determined by the noise in the all-sky mosaic maps. In order to measure the noise and determine the sensitivity, we use the method described in Section 4.3 of calculating the local rms level from the maps in the area around each source. The sensitivity is then calculated in Crab units using the measured count rate of the Crab given in Table 2. Figure 10 shows the distribution of sensitivities measured in pixels from the all-sky mosaicked map. The median $5\sigma$ sensitivity achieved in the 70 month survey is 0.43 mCrab, or $1.0 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 14–195 keV band.

We can now compare the measured sensitivity achieved in the survey to the predicted level computed with Equation (9). Taking the ratio of the 0.38 mCrab median predicted sensitivity to the 0.43 mCrab median measured sensitivity ($0.43/0.38 \approx 1.13$), we find that the BAT 70 month survey achieves a sensitivity level within 13% of the theoretically ideal performance. In comparison, the BAT 22 month survey achieved a sensitivity within 40% of expectations. This advance in achieved sensitivity between the 22 and 70 month surveys can be attributed to the improvements in the survey data reduction and processing described in Section 3.

Figure 11 shows the relationship between the measured sensitivity and the predicted sensitivity for all four installments of the Swift-BAT survey. The black dashed line in the figure gives the theoretical survey sensitivity as predicted by Equation (9). The contours show the measured sensitivities for the pixels in the all-sky map. The red contours are from the 3 month survey, the green contours from the 9 month survey, the blue contours from the 22 month survey, and the purple contours from this work. The 70 month contours are much closer to the dashed predictions than the 22 month contours, again showing the improvements made in the 70 month data reduction and processing. The small tails in the contours at lower exposure and sensitivity are from areas near the galactic center that suffer from higher systematic noise.

The difference between the theoretical sensitivity and the measurements increases slightly at longer times (for the 3, 9, and 22 month samples) because the systematic errors are not decreasing with time the same way that the statistical errors are. The 70 month measured data shows sensitivity closer to the theoretical expectation. This is because the newly implemented data processing pipeline for the 70 month survey improves the sensitivity and reduces systematic errors resulting from problems like uncorrected pixel gain shifts.
Figure 11. Measured 5σ BAT sensitivity limit for pixels in the all-sky map as a function of effective exposure time, $T$, for the 3 month (red; Markwardt et al. 2005), 9 month (green; Tueller et al. 2008), 22 month (blue; Tueller et al. 2010), and 70 month (purple) survey analyses. The contours are linearly spaced and indicate the number of pixels with a given sensitivity and effective exposure. The black dashed line represents a lower limit to the expected Poisson noise level (see Section 5.2). The median achieved sensitivity is within 13% of the predicted value.

(A color version of this figure is available in the online journal.)

6. CONCLUSIONS

The Swift-BAT 70 month catalog is the fourth published catalog compiled from sources detected in the Swift-BAT all-sky hard X-ray survey. This most recent version of the official Swift-BAT survey catalog contains 1171 sources (associated with 1210 counterparts) detected across the entire sky and is the deepest uniform hard X-ray survey ever conducted.

With detections of over 600 AGN in the hard X-ray band, the Swift-BAT 70 month survey catalog contains a valuable reference set of active galaxies in the local universe. In addition to the survey catalog, the database of hard X-ray spectra and light curves from throughout the Swift mission will be an important source of information for future studies of galactic hard X-ray sources and AGNs.

We acknowledge the help of Mike Koss in obtaining optical spectra and redshifts for many sources in the table. This work has made heavy use of the NED, SIMBAD, and HEASRAC online databases as well as the private Leicester database of automatic analyses of XRT data for the follow-up observations of the BAT survey sources. And of course, this work could not have been completed without the diligent effort of all the members of the Swift team. Additionally, P.A. E. acknowledges support from UKSA.

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