The Accuracy of GBM GRB Locations

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Abstract. The *Fermi* Gamma-Ray Burst Monitor (GBM) locates transient gamma-ray sources using the relative rates in the twelve NaI detectors. The location algorithm is described. This method is subject to both statistical and systematic errors. Three types of locations are produced: automatic locations by the Flight Software onboard GBM, automatic locations by ground software, and human-guided locations. A Bayesian model comparison method is used to analyze the error distributions of the GBM GRB locations. The analysis uses samples of accurate reference locations provided by other instruments.

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GBM LOCATION METHOD

GBM Instrument and Locations

The Gamma-Ray Burst Monitor (GBM) on the *Fermi* Gamma-ray Space Telescope has twelve NaI and two BGO scintillation detectors to view 9 steradians, essentially the entire unocculted sky. The NaI detectors are 1.27 cm thick by 12.7 cm in diameter and cover the energy range 8 keV to 1 MeV; they are arranged in four clusters of three, each detector pointing in a different direction. The signals from the NaI detectors are used to locate transient gamma-ray sources such as gamma-ray bursts. The BGO detectors cover the energy range 150 keV to 40 MeV; these data are currently not used in determining source locations [1].

The GBM scintillation detectors are not imaging detectors and individually provide no directional information. Collectively the signals from the set of NaI detectors can be used to deduce the direction to a gamma-ray source. Because the NaI detectors are relatively thin, they have an approximately cosine response as a function of source position off-axis. Since the detectors point in different directions, a source will have differing rates in the various NaI detectors. Comparing these rates allows the determination of the source location. This method was used by the original series of KONUS instruments [2] and by BATSE [3].

This method has the advantage that it can produce locations over a very wide field-of-view, but has the limitation that the accuracy is of degree scale. The location accuracy is limited by statistical fluctuations in the number of photons detected by the detectors, both in the source interval and in the intervals used to determine the background, and by systematic errors. Systematic errors include incorrect modeling of the background or of the spectrum of the source, inaccuracies in the conversion of channels to energy, imperfect modeling of the response of the detector, either in direction or energy, and imperfect modeling of scattering of radiation into the detector from the Spacecraft and the Earth's atmosphere.

The purpose of this paper is to quantify the accuracy of the GRB locations that have been produced by GBM through 2009 February 15. Locations from other types of sources are not analyzed herein – the various spectra of these source classes might result in different location errors.

Location Algorithm

Three types of locations are produced for GBM sources: the Flight Software (FSW) on-board GBM calculates and outputs locations in near real time. The FSW also outputs priority near real-time telemetry data that are used by

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automatic ground software to calculate and output locations. Both of these location types are promptly output via the Gamma-ray bursts Coordinate Network (GCN) [4] as automatic Notices. The high-priority telemetry is also processed by humans, to produce locations based on a more careful selection of source and background time intervals. These locations are published via the GCN as human-written Circulars, after a delay of tens of minutes to a day or more.

The algorithms used by the FSW and by the ground software to calculate locations from the detector rates are conceptually similar but differ in details.

Locations are based on rates in the 50 to 300 keV band. The interval for the source rates is selected by the FSW to maximize signal-to-noise ratio (SNR). Accumulations from 16 ms to 4 s are evaluated for SNR. The background model is the average of a 17 s long data interval that ends ≈ 4 s before the trigger time.

The FSW location algorithm is simple and robust. Stored onboard the Flight Data Processing Unit (DPU) is a table of detector rates, precomputed for a grid of locations in spacecraft coordinates. The algorithm consists of comparing the observed rates to the precomputed rates and selecting the best match in the χ^2-sense. The precomputed table contains rates for all 12 NaI detectors for 1634 grid points covering the sky, with a typical spacing of 5°.

Due to the limited memory of the Flight DPU, only one table of precomputed locations can be stored. The detector rates in that table were calculated for a typical GRB spectrum: $E_{\text{peak}} = 230$ keV, $\alpha = -1.0$ and $\beta = -2.3$ in the standard Band GRB function [5]. The detector rates in the table include spacecraft and atmospheric scattering, but since there is only a single table, the rates can only be for a single spacecraft orientation. As the best compromise, the table was calculated for the LAT pointing at the zenith. However, that is an uncommon orientation for *Fermi* – the normal operating mode, to survey the sky, is to alternate orbits tipped North and South of the zenith by 35°.

The FSW location algorithm reports an estimate of the total location error, including the systematic error.

Like the FSW algorithm, the ground locations are based upon the observed rates in the 50 to 300 keV energy range.

The ground location algorithm is also table based, but the larger memory available allows better tables. There are three tables, for soft, typical and hard GRB spectra. The software selects the table of pre-computed rates to compare to the observed rates based upon a hardness ratio of the observed signal. Each table has 41,168 locations covering the sky with 1° spacing. The pre-computed rates in each table include both the direct response of the detectors to the GRB spectrum and the response to the flux scattered from the spacecraft. At runtime the ground software calculates an approximate contribution from scattering from the Earth's atmosphere using the actual geometry of the GRB.

The methods of producing human-guided and automatic ground locations differ only in the selection of the data. The automatic locations use Maximum Rates selected by the FSW by SNR from 50 to 300 keV on timescales from 16 ms to 4 s. The automatic locations use the same simple background model that the FSW uses for the onboard locations. The principal difference in human-guided locations is that human judgement is used in selecting source and background intervals. These intervals can be longer than those used by the automatic algorithms and the background model can be based on two intervals that straddle the source interval. The background data is fit with a low-order polynomial to model the time variations, rather than merely being an average of the data.

Another difference is that the location error reported by the ground-based software is intended to be statistical only. The statistical error is derived as the radius of the circle that has the same area as the region enclosed by the χ^2 contour that is 2.3 above the minimum. Currently the GBM Team suggests that an additional systematic error of 2 to 3 degrees should be added to human-guided locations (typical text of GBM GCN Circulars) – this paper will test this prescription.

LOCATION ACCURACY

Method of Determining Location Accuracy

We test the accuracy of GBM GRB locations by comparing the GBM locations to more accurate locations produced by other instruments. Reference locations include locations that are essentially "points" compared to the accuracy of GBM: these reference locations are obtained from the Swift BAT, XRT and UVOT instruments, INTEGRAL IBIS, Super-AGILE, the *Fermi* Large Area Telescope (LAT) and ground based telescopes. Another type of reference location is single IPN arcs; only arcs with 3σ half-widths of 0.5° or smaller are used so that the uncertainty of the IPN position, in one dimension, is much less than that of the GBM location. In the future the samples will include IPN error boxes resulting from intersecting arcs.

An offset for a particular GRB between the GBM location and an accurate reference location might be due to Poisson fluctuations in the counts recorded by the GBM detectors, or might be indicative of some systematic error. Only by analyzing the entire sample of GBM GRBs with accurate reference locations can we constrain the location error model. This paper applies a Bayesian analysis, in which several models for the location error probability distribution are compared to select the model which is favored. The Bayesian method starts with the probability density functions for various models and computes the likelihoods of the models. This method is able to combine the information of point and IPN arc reference locations. The method also includes an "Occam's Factor" which penalizes models that have more parameters. The method was used to analyze the location error distribution of BATSE locations, and is described in more detail in that paper [6].

Test Samples and Results

The two samples have different GBM locations: one has GBM FSW locations, the other human-guided ground locations. They also differ in membership: the first FSW version produced useful locations but inaccurate locations errors – these FSW errors are not worth testing. The FSW location sample begins with the installation of FSW version 2.2 (FSW Location Algorithm 3) on 2008 October 1, which produces valid location errors.

The sample for the FSW includes all GRBs from 2008 October 1 to 2009 February 15 with accurate reference locations. The "point location" portion of this sample consists of 17 GRBs, from 2008 October 8 to 2009 January 17. The sample also includes four GRBs for which IPN arcs are available: GRBs from 2008 October 9 to 2009 January 8. The GBM location used is the last location produced by the FSW for a particular GRB.

FSW 2.2 (Location Algorithm 3) reports an estimate for the total error, not an estimate of the statistical error. A σ_{sys} term is already included in the error estimate of the FSW – the expected result of modeling the location error distribution of FSW locations is that there should be no need for an additional σ_{sys} term.

The Bayesian analysis of the sample for the FSW locations obtains $\sigma_{sys} = 5.8^\circ \pm 1.5^\circ$ degrees, but the discrepancy is due to a single outlier, GRB 081215A (081215.784). Removing this single outlier from the sample results in $\sigma_{sys} = 3.1^\circ \pm 3.1^\circ$, with negligible evidence for this model – an Odds Ratio of only 1.8.

Excepting only GRB 081215A, the location errors reported by the FSW are consistent with not needing to add an additional σ_{sys}. This means that the FSW locations errors are working as designed, since the location errors reported by the FSW are intended to be total error values rather than just statistical errors.

The sample for human-guided locations includes all GRBs with accurate reference locations from the enabling of triggering on 2008 July 14 to 2009 February 15. The sample consists of 30 point reference locations, with GRBs from 2008 July 14 to 2009 January 17, and six GRBs with reference IPN Arcs, from 2009 August 16 to 2009 January 08.

The result of the Bayesian analysis of this sample is $\sigma_{sys} = 3.8^\circ \pm 0.5^\circ$ (preferred over omitting an additional systematic error by an enormous Odds Ratio, $10^{43.7}$). The human-guided location analysis produced a much better location for GRB 0801215.784, which is therefore not an outlier and the results are essentially unchanged if it is removed from the sample. The value found for σ_{sys} for the human-guided locations is somewhat larger than was found in an earlier, unpublished analysis that was made with a smaller sample. That analysis found $\sigma_{sys} = 2^\circ$ to 3°.

The analysis of BATSE location errors showed more complex models of the error distribution to be strongly preferred according to the data, such as a model in which the error distribution had a systematic error of 1.85° with probability 78% and 5.1° with the remaining probability [6]. Currently the Bayesian analysis of the GBM location samples does not favor models more complicated than a single σ_{sys} value. This is likely due to the small size of the samples – in modeling the BATSE location error distribution it was found that ~ 50 reference locations are needed per error model parameter [6]. When larger reference samples are available they may indicate a more complex model, either a two-component σ_{sys} model, or perhaps a model in which the location error has a dependence on a GRB parameter, such as hardness or position in spacecraft coordinates.

The GBM Team is working on improving the location algorithms with the goal of improving location accuarcy.

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