Determining Spatial Extendedness of GLAST Sources

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>2</td>
</tr>
<tr>
<td>Results</td>
<td>5</td>
</tr>
<tr>
<td>Discussion</td>
<td>7</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>9</td>
</tr>
<tr>
<td>References</td>
<td>9</td>
</tr>
<tr>
<td>Figures</td>
<td>11</td>
</tr>
</tbody>
</table>
ABSTRACT

Determining Spatial Extendedness of GLAST Sources. ADAM J. ZOK (University of California at Berkeley, Berkeley, CA 94720) MARKUS M. ACKERMANN (Stanford Linear Accelerator Center, Menlo Park, CA 94025).

In order to identify the origin of photons detected by the Gamma-ray Large Area Space Telescope (GLAST), an effective method for classifying and parameterizing astrophysical objects as point sources or spatially extended sources is desired. GLAST software package Gtobssim is used to simulate the detector’s interpretation of various types of gamma-ray emitters, and sourcefit is used to reconstruct parameters for the sources using these simulated files. Fits were run using many different settings available in sourcefit to determine how to use the program most effectively, and sources of various sizes, fluxes and spectra were modeled to determine the parameter limits for this analysis. No compelling reason was found to change the default values of sourcefit’s settings, and fit quality was discovered to improve significantly with increasing flux and decreasing spectral index. Test Statistic (TS) value was seen to decrease rapidly as spectral index increased, suggesting that soft spectrum sources are more difficult to parameterize due to more of their photons being mistakenly characterized as background radiation. Future research should include testing in the presence of more realistic background radiation, as well as a more descriptive quantification of sourcefit’s accuracy.
INTRODUCTION

The Gamma-ray Large Area Space Telescope (GLAST) is a new and very exciting instrument to members of the observational astronomy community. Launched into Earth's orbit on June 11, 2008 after over a decade of careful planning and international collaboration, the telescope is expected to study some of the most energetic astronomical sources known, such as active galactic nuclei, pulsars, supernova remnants, gamma-ray bursts, and perhaps even the annihilation of dark matter particle / anti-particle pairs [1]. Because GLAST detects photons in a higher energy range (30 MeV – 300 GeV) and exhibits superior angular resolution and sensitivity compared to its predecessor, the Energetic Gamma Ray Experiment Telescope (EGRET), these sources can soon be studied in ways that were not previously possible [1].

Regardless of which objects astronomers choose to focus their studies on, reliable source identification will be essential to almost any research performed using GLAST data. This is a nontrivial task due to GLAST’s limited spatial resolution (0.15° – 3.5°, depending on photon energy), which is characterized by its Point Spread Function (PSF) [1]. As a result of this uncertainty, several astrophysical sources are typically found within the positional error of the gamma-ray detector which could have potentially emitted the detected photons. Because spatially extended sources (those having a measurable angular size) are much less commonly observed than point sources, identifying a source as being spatially extended is an effective way of narrowing down the list of candidate objects quite significantly. The main goal of this research project is to be able to consistently distinguish between point sources and spatially extended sources, and to investigate the limits in the flux, spectrum, and size of such sources to which this classification can be performed.
MATERIALS AND METHODS

As we now live in the digital age, modern astronomy no longer involves looking into the eyepiece of a giant optical telescope, but instead relies heavily on computer-based analysis. Ordinary desktop computers, combined with the Stanford Linear Accelerator Center’s (SLAC) batch farm of several hundred CPUs, allow large data simulations and analysis operations to be performed using the GLAST software packages *gtobssim* and *sourcefit* [2]. *Gtobssim* is a program that creates virtual gamma-ray emitters according to user-specified parameters (such as shape, flux, spectrum, position and size), and outputs an event file representative of how GLAST may have observed the simulated sources (see Figure 1). These data files are in the Flexible Image Transport System (.fits) format, which is the standard file type that both NASA and the International Astronomical Union use to store their astronomical data. Thus, the simulated event files can be analyzed with almost the exact same methods that are used for actual GLAST data. Another extremely useful program, *sourcefit*, is used to determine the position, spectrum and spatial extension of the candidate source most likely to have created the gamma-rays that GLAST records (or those simulated by *gtobssim*). At this time, it is generally functional although certain components of it are still under development. Given an event file, *sourcefit* computes the likelihood of different parameter hypotheses, which it expresses to the user as a Test Statistic (TS) value (a measure of fit quality). The program starts with the user's best guesses for the parameters of the source, and runs through an optimization process until the combination of parameters leading to the highest TS value is identified.

*Sourcefit* outputs two .fits files containing all of the data describing the best fit distributions, making the fitted models convenient to analyze. In addition to reporting the optimized values for the various fit parameters, *sourcefit* also provides confidence limits for some of the more critical parameters, such as the position, size, and number of detected photons.
thought to have originated from the source under investigation (as opposed to background radiation). Popular Python modules such as PyFITS and ROOT can be used to read and plot the fitted data, and to determine for which types of sources and ranges of source parameters \textit{sourcefit} is able to model a close fit for [3].

Since it had not yet been determined how well \textit{sourcefit} is able to parameterize sources of different shapes, fluxes, sizes and spectra, numerous arrays of simulated sources were created, varying at most two parameters at a time (one for each dimension of the array), which were then run through \textit{sourcefit}. Having the luxury of knowing the exact parameters used to generate the simulated event files meant that the fitted models could be compared to the actual source distributions, which served as a check of whether or not \textit{sourcefit} was correctly modeling the data. To analyze the accuracy of the fits, the values of useful quantities were calculated (such as \textit{sourcefit}'s errors in size and position, total TS values, and the number of photons in different energy ranges) and plots were generated to make the data more easily interpretable.

Analysis was initially focused on ten different simulated spatially extended sources, with parameters similar to those of the sources that GLAST is actually observing. Specifically, Gaussian-distributed sources of sizes 0.05, 0.10, 0.30, 0.95, and 1.05 degrees were used, simulated at two different flux levels (“size” and “standard deviation” are used interchangeably throughout this paper). Because \textit{sourcefit} is very new and still under development at the time of this writing, one of the first things that needed to be done was to determine how to most effectively use the program as a modeling tool. \textit{Sourcefit} separates the photons it analyzes into different energy bins for its analysis, taking into account the PSF for photons of different energies. The program was run on the same sources many times over, using various values for both the number of energy bins used the energy range taken into consideration for the fits (see Figures 2 and 3). In addition, there are two optimization algorithms that \textit{sourcefit} can make use
of, Minuit and Simplex, and fits were performed using both in order to investigate their
differences. Since small changes were being made to the program on an almost daily basis, in
many instances the models produced were unsatisfactory and it was necessary to run the fits
again using an updated version of the program.

Once the program had matured to the point where it was able to produce reasonably close
fits in most instances, testing under more challenging conditions became possible. In order to
produce accurate models, it is extremely important that sourcefit is able to correctly distinguish
its target objects from other sources of gamma-ray radiation. To test its capabilities, a model of
the diffuse extragalactic gamma-ray radiation was superimposed over the simulated sources that
the program was fitting, sourcefit was forced to subtract the background radiation before
modeling the sources. Again, fits were run using many different combinations of settings in
order to determine the most effective way to use the program.

After the optimal settings were found for sourcefit to produce accurate fits in the case
where the target sources are obscured by a diffuse background, the next logical step was to
determine the limits in size, spectrum and flux for which sourcefit could no longer be relied upon
to produce accurate results. However, each limit changes when different values for the other
parameters are used, so the limits cannot be found by simply performing three independent
analyses. Because of this, 4 new event files were simulated, each containing 72 Gaussian-shaped
sources arranged in a 12 x 6 grid. In the wider direction, the standard deviations of the sources
range in value from 0.05° – 0.90°, and in the other the spectral indices range from 1.0 – 3.0. The
event files differed from each other only in the flux of the sources they were simulating, which
ranged between $3 \times 10^{-5} \text{ s}^{-1} \text{ m}^{-2}$ and $10^{-3} \text{ s}^{-1} \text{ m}^{-2}$ for photons above 100 MeV. Thus, all 4 event files
considered together effectively create a three-dimensional space in size, spectrum and flux,
containing 288 test sources for sourcefit to model.
To determine the parameter limits at which these fits break down, a quantitative way of describing what constitutes an acceptable model needed to be settled upon. Knowledge of GLAST’s capabilities and intuition gained from analyzing dozens of fits ultimately led to the following set of criteria: a fitted standard deviation within either 3’ (arcminutes) or 20% of the actual value and a fitted position within 5’ + 20% of the source’s size (in both right ascension and declination) are considered successful models. Because a combination of fractional and absolute error is used, these criteria can be applied to sources of all sizes without overwhelming bias towards small or large sources. To better visualize the data, plots were created for each flux level, plotting size and spectrum along the two axes. These plots showed whether each combination of parameters led to a valid or invalid fit, considering size and position separately. Furthermore, checks were made to see whether or not size and position were fitted within the program’s calculated confidence levels, and more plots were created to display this information. In addition to these spatially extended distributions, an array of point sources was created with fluxes ranging from $3 \times 10^{-5} \text{s}^{-1} \text{m}^{-2}$ – $3 \times 10^{-3} \text{s}^{-1} \text{m}^{-2}$ and spectral indices ranging from 1.0 – 3.0, and tests were run to see whether or not Minuit and Simplex are able to correctly identify them as point sources.

RESULTS

Sourcefit’s performance in determining the standard deviations of 10 different test objects is shown in Figure 2. Fits considering 4 different energy ranges of data were performed on each of the 10 sources, and graphs plotting the modeled size versus the actual size show how accurately each fit was able to reconstruct the sources it was analyzing. As previously mentioned, both faint and bright Gaussian sources of 5 different sizes were analyzed so that sourcefit could be tested on a varied set of objects. All sources had a spectral index of $\Gamma = 2$. 
The plots shown in Figure 3 consider the five high flux Gaussian sources used to create Figure 2, and the sources are analyzed using the two energy ranges which were found to produce the most accurate results. Fits using 5 different energy binning methods were performed on all 5 sources for both energy ranges, and the fitted size versus actual size was plotted to show the difference in performance of the various binning methods.

The ability of sourcefit to parameterize the 12 x 6 x 4 array of Gaussian sources of various sizes, specta and fluxes is depicted by Figures 4-12. Figures 4 and 5 show which sources were modeled with an acceptable standard deviation by Minuit and Simplex, while Figures 6 and 7 do the same for position. The two algorithms performed with comparable accuracy for fitting sources of all sizes and spectra. Fit quality was found to be strongly correlated to source flux and spectral index, as bright, low-$\Gamma$ sources are much more successfully modeled than dim, high-$\Gamma$ sources. Sources with fluxes of $3 \times 10^{-5}$ s$^{-1}$m$^{-2}$ and $10^{-4}$ s$^{-1}$m$^{-2}$ appear to have an upper limit of $\Gamma = 1.0$ for accurately parameterized standard deviations, while sources with fluxes of $3 \times 10^{-4}$ s$^{-1}$m$^{-2}$ and $10^{-3}$ s$^{-1}$m$^{-2}$ had an upper limit of $\Gamma = 2.2$. The spectral indices below which sources could be accurately located were found to be 1.0, 1.8, 2.6 and 3.0 or higher, rising with each incremental increase in flux.

The reliability of the confidence limits for size and position is shown by Figures 8-11. Both algorithms performed quite poorly, although Simplex fits had noticeably fewer incidences of error bars extending unreasonably far from the fitted parameters, and can be considered to work slightly better in this respect. The calculated confidence limits appeared to improve as flux increased, but never reached the point where they could be considered meaningful. Figure 12 plots the relationship between TS value and both source size and spectral index, using data from a Simplex fit on an array of sources with flux = $10^{-3}$ s$^{-1}$m$^{-2}$. TS value is seen to decrease with both increasing source size and spectral index. Lastly, Figures 13 and 14 show the capabilities of
Minuit and Sourcefit to identify point sources of various spectra and fluxes, and Minuit’s superiority at this task is evident.

**DISCUSSION**

The data used to create Figure 2, along with other plots not shown here, does not suggest that any of the alternative energy ranges exhibit superior performance to the default range. The default range generally gives above average performance compared to the other ranges under a wide variety of conditions, and therefore was the only range used in some of the later analyses. However, it should be noted that the simulated files contain photons with energies between 100 MeV – 1 TeV, while the default energy range spans only from a few hundred MeV – 1 TeV (the exact range depends on the energy bins used and whether the photons pair-produced in the front or back of the detector). It is important to note that the number of photons at a given energy is described by a power law of the form \( N_E = A E^{-\Gamma} \), where \( N_E \) is the number of photons, \( E \) is the energy, \( \Gamma \) is the spectral index, and \( A \) is a constant of proportionality. As a result, sources with a high spectral index will have many of their photons excluded from analysis by the default energy boundaries. Since GLAST’s spatial resolution worsens significantly for low energy photons, this exclusion is generally helpful as it allows fits to be run using a higher quality set of data. However, *sourcefit* users investigating low flux, high-\( \Gamma \) sources may want to consider relaxing their lower energy boundary in order to work with a more statistically significant number of data points.

The results plotted in Figure 3 reveal no reason to use any of the customized energy binning methods instead of the default method, since it appears as if the user-specified energy bins generally lead to poorer fits as the standard deviation of the examined source becomes larger. Especially in the 100 MeV – 100 GeV case, it is evident from the graphs that the fits
using user-specified energy bins produced very similar results to one another, even when this was different from the results found by using the default energy bins. This is due to the fact that sourcefit actually uses a slightly different fitting algorithm when anything other than the default bins are used. Unfortunately, this behavior was not known about until all of the data had been gathered, and the inclusion of this additional variable was unable to be accounted for.

The fact that sourcefit is only able to correctly model sources of a given spectral index above a minimum flux level (see Figures 4-7) suggests that the presence of a significant number of high energy photons is necessary for the program to work properly. This is supported by Figure 12, which shows TS values dropping off rapidly as spectral index increases. For Gaussian statistics,

\[ TS \approx \frac{N_S^2}{N_B}, \]

where \( N_S \) is the number of photons detected from the source and \( N_B \) is the number of photons attributed to the background radiation. Since all of the sources in Figure 12 are of the same flux, a decrease in TS corresponds to more photons being considered to be part of the background. The apparent dependence TS exhibits on source size and spectral index makes sense, since it seems intuitive that more photons would blend in with the background radiation as they become spread out over an increasingly large area on the sky. Furthermore, the greater influence of spectral index on TS compared to that of source size is expected, as the PSF of low energy photons (around 3.5°) is much greater than the standard deviation of any of the sources examined in these arrays.

Since sourcefit still has a long period of development ahead of it before it can be considered a finished analysis tool, the possibilities for future work are almost endless. The inability of sourcefit to determine reasonable confidence limits for its models stems from known problems with the error matrix used to calculate these values, making it an obvious target for
further refinement. Eventually, *sourcefit* is going to need to be tested under harsher, more realistic conditions, such as modeling sources with less regular spectra (following a broken power law, for example) in the presence of background gamma-ray sources located within the Milky Way. As the program’s development nears its end, it will need to be tested using many more simulations than were used in this analysis in order to rule out any statistical irregularities that may be introduced by *gtobssim*. Furthermore, plots that more descriptively quantify *sourcefit*’s ability to parameterize different types of sources (as opposed to simply designating fitted values as being within or outside of the acceptable range) may prove to be useful in determining whether Minuit or Simplex should be used when modeling actual GLAST sources.

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REFERENCES


Figure 1: An example of a photon map corresponding to an event file generated from 72 simulated gamma-ray sources. This represents the data that GLAST might record from the sources, not the photons that are actually emitted. Spatial extent increases to the left, and spectral index increases in the upward direction. A higher spectral index corresponds to a lower average photon energy, which inhibits GLAST’s ability to track the direction of the incoming photons. This is evidenced by the blurring of the sources at the top of the image.
Figure 2: Simplex size fitting results for a variety of energy ranges in the presence of diffuse extragalactic background radiation. Red, brown, green, and blue represent the default, 100 MeV – 100 GeV, 500 MeV – 100 GeV, and 1 GeV – 100 GeV energy ranges respectively. Confidence limits are shown for the 100 MeV – 100 GeV energy range only. The straight line denotes a perfect fit.

(a) Flux = $10^{-4} \text{s}^{-1} \text{m}^{-2}$ (b) Flux = $10^{-3} \text{s}^{-1} \text{m}^{-2}$
Simplex Energy Bin Testing

Figure 3: Simplex size fitting results for high flux \(10^3 \text{s}^{-1} \text{m}^{-2}\), \(\Gamma = 2\) sources in the presence of diffuse extragalactic background radiation, using a variety of energy binning methods. Red represents the default binning, while brown, green, blue and pink represent 2, 3, 4, and 6 logarithmically spaced bins per decade respectively. Confidence limits are shown for the default binning only. The straight line denotes a perfect fit.

(a) Default energy range is used. (b) 100 MeV – 100 GeV range is used.
Minuit Size Fitting Results

Figure 4: Green points represent sources for which Minuit modeled a size within the acceptable range (an error of 3’ or 20% of the true value, whichever is greater), and red points represent unacceptable fits.

(a) Flux = $3 \times 10^{-5} \, \text{s}^{-1} \, \text{m}^{-2}$  (b) Flux = $10^{-4} \, \text{s}^{-1} \, \text{m}^{-2}$  (c) Flux = $3 \times 10^{-4} \, \text{s}^{-1} \, \text{m}^{-2}$  (d) Flux = $10^{-3} \, \text{s}^{-1} \, \text{m}^{-2}$
Figure 5: Green points represent sources for which Simplex modeled a size within the acceptable range (an error of 3’ or 20% of the true value, whichever is greater), and red points represent unacceptable fits.

(a) Flux = $3 \times 10^{-5} \text{s}^{-1} \text{m}^{-2}$  (b) Flux = $10^{-4} \text{s}^{-1} \text{m}^{-2}$  (c) Flux = $3 \times 10^{-4} \text{s}^{-1} \text{m}^{-2}$  (d) Flux = $10^{-3} \text{s}^{-1} \text{m}^{-2}$
Minuit Position Fitting Results

Figure 6: Green points represent sources for which Minuit fitted a position within the acceptable range (an error of 5’ + 20% of the source’s size), and red points represent unacceptable fits.

(a) Flux = 3 \times 10^{-5} \text{ s}^{-1}\text{m}^{-2}  (b) Flux = 10^{-4} \text{ s}^{-1}\text{m}^{-2}  (c) Flux = 3 \times 10^{-4} \text{ s}^{-1}\text{m}^{-2}  (d) Flux = 10^{-3} \text{ s}^{-1}\text{m}^{-2}
Simplex Position Fitting Results

Figure 7: Green points represent sources for which Simplex fitted a position within the acceptable range (an error of 5’ + 20% of the source’s size), and red points represent unacceptable fits.

(a) Flux = 3 x 10^{-5} \text{s}^{-1} \text{m}^{-2}  
(b) Flux = 10^{-4} \text{s}^{-1} \text{m}^{-2}  
(c) Flux = 3 x 10^{-4} \text{s}^{-1} \text{m}^{-2}  
(d) Flux = 10^{-3} \text{s}^{-1} \text{m}^{-2}
Figure 8: Green points represent sources for which Minuit modeled a size within its calculated confidence limits, and red points represent fits outside of the confidence limits. Black points represent sources that were calculated to have an uncertainty greater than their fitted size.

(a) Flux = $3 \times 10^{-5} \text{ s}^{-1} \text{ m}^{-2}$  (b) Flux = $10^{-4} \text{ s}^{-1} \text{ m}^{-2}$  (c) Flux = $3 \times 10^{-4} \text{ s}^{-1} \text{ m}^{-2}$  (d) Flux = $10^{-3} \text{ s}^{-1} \text{ m}^{-2}$
Figure 9: Green points represent sources for which Simplex modeled a size within its calculated confidence limits, and red points represent fits outside of the confidence limits. Black points represent sources that were calculated to have an uncertainty greater than their fitted size.

(a) Flux = $3 \times 10^{-5}$ s$^{-1}$m$^{-2}$ (b) Flux = $10^{-4}$ s$^{-1}$m$^{-2}$ (c) Flux = $3 \times 10^{-4}$ s$^{-1}$m$^{-2}$ (d) Flux = $10^{-3}$ s$^{-1}$m$^{-2}$
Reliability of Minuit Confidence Limits for Position

Figure 10: Green points represent sources for which Minuit fitted a position within its calculated confidence limits, and red points represent fits outside of the confidence limits. Black points represent sources that were calculated to have an uncertainty greater than 1°.

(a) Flux = $3 \times 10^{-5} \text{s}^{-1}\text{m}^{-2}$  (b) Flux = $10^{-4} \text{s}^{-1}\text{m}^{-2}$  (c) Flux = $3 \times 10^{-4} \text{s}^{-1}\text{m}^{-2}$  (d) Flux = $10^{-3} \text{s}^{-1}\text{m}^{-2}$
Reliability of Simplex Confidence Limits for Position

Figure 11: Green points represent sources for which Simplex fitted a position within its calculated confidence limits, and red points represent fits outside of the confidence limits. Black points represent sources that were calculated to have an uncertainty greater than 1°.

(a) Flux = $3 \times 10^{-5} \text{ s}^{-1} \text{m}^{-2}$  (b) Flux = $10^{-4} \text{ s}^{-1} \text{m}^{-2}$  (c) Flux = $3 \times 10^{-4} \text{ s}^{-1} \text{m}^{-2}$  (d) Flux = $10^{-3} \text{ s}^{-1} \text{m}^{-2}$
Figure 12: TS values calculated from a Simplex fit are plotted as a function of spectral index and standard deviation for the case where flux = $10^{-3} \text{ s}^{-1}\text{m}^{-2}$.
Figure 13: Green points represent point sources that Minuit fitted to a Gaussian model with a standard deviation less than 0.001°, blue points represent sources with a fitted standard deviation from 0.001° - 0.01°, and red points represent sources with a fitted standard deviation greater than 0.01°.
Figure 14: Green points represent point sources that Simplex fitted to a Gaussian model with a standard deviation less than 0.001°, blue points represent sources with a fitted standard deviation from 0.001° - 0.01°, and red points represent sources with a fitted standard deviation greater than 0.01°.