# Multicomponent modelling of the gamma-ray background

Z. Bagoly,[1] P. Veres,[2] L. G. Balazs,[3] D. Szécsi,[4,5] L. V. Tóth,[3] S. Pinter,[6] I. I. Racz[6] and I. Horvath,[6]

[1] Department of Physics of Complex Systems the Eötvös University, Budapest, Hungary [2] CSPAR, University of Alabama in Huntsville, Huntsville, AL, USA [3] Department of Astronomy of the Eötvös Loránd University, Budapest, Hungary [4] I. Physikalisches Institut, Universität zu Köln, Germany [5] Institute of Astronomy, Nicolaus Copernicus University, Torun, Poland [6] University of Public Service, Budapest, Hungary

DEPARTMENT OF SPACE SCIENCE
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

## Introduction

The accurate background estimation is a key element for weak transients detection in the multi-detector/multi-chanell environment. Well handled signal backgrounds will enhance the sensitivity, while allowing off-line searches (e.g. Gruber & Fermi/GBM Collaboration (2012)) for weak, long and slow transients which will not trigger the onboard mechanism. The detection of a very weak and short signals near the instrument's energy boundaries (i.e. the very soft or very hard transients) could be also improved by the right background model.

It is hard to model the gamma-ray background observed by all-sky spaceborn detectors due to it's complex nature. These detectors usually cover the whole sky, therefore both diffuse and point sources contribute to the observed counts. Here we investigatet the Fermi Gamma-ray Burst Monitor (GBM). For the GBM the satellite's specific motion further complicates the signal as the spacecraft continously sweeps to survey the sky.

The Fermi GBM detector system consists of 12 NaI(Tl) and two Bismuth Germanate (BGO) scintillators, observed by photomultipliers (Meegan et al. 2009). The NaI(Tl) detectors cover the low-energy (8 keV to ~ 1 MeV) spectrum while the BGO detectors are sensitive in the energy range of ~ 200 keV - ~ 40 MeV. Since November 2012, the GBM CTTE (continuous time-tagged event) data is stored for each photon for each detector and energy channel, with a time resolution of 2 µs.

The photomultipliers' signals are analyzed with a pulse height analysis and the height of a given impulse will be stored into one of the 128 channels. The function between the incoming photon energy and the channels are linear, described by the DRM detector response matrix. This matrix depends on the geometry (angular dependence of the efficiency, energy deposition and dispersion, atmospheric and spacecraft scattering).

The background problem is further complicated by the fact that the events are correlated between the detectors and channels implicitly. The field of views of the detectors are overlapping and the DRM's are only slightly different for detectors facing similar directions.

The background estimation problem is to find the best approximation of this correlated, quite spare multi-detector multi-channel time series in a time interval (i.e. during the transient), with data from the pre- and post interval only. This complex job of course has several solution, some methods were developed especially for the Fermi Gamma-ray Burst Monitor.

## Background estimation with the rmfit package

The typical GRB event is short, usually below 100sec, while the usual variation timescale of the background is about ten times longer. Therefore the simple polynomial fitting is usually adequate. The CGRO/BATSE DISCSC background data were estimated with a second or third order polynom.

Similarily the Fermi's `rmfit` package also uses this generic method. For a given search interval two regions should be selected, usually one before and and one after the transient. The exact selections depends on the user (the manual observes: "*Deciding how much background to choose comes down to experience*"). This can help with longer events and/or rapidly varying background, but hard to automatize. The software approximates the background for every detector and for every chanel (with a resolution either 8 or 128 PHA range) with some low order polynom.

As an example we show the background estimations for the GRB091030 event (Figs. 1-3), where after the trigger the satellite rotated.

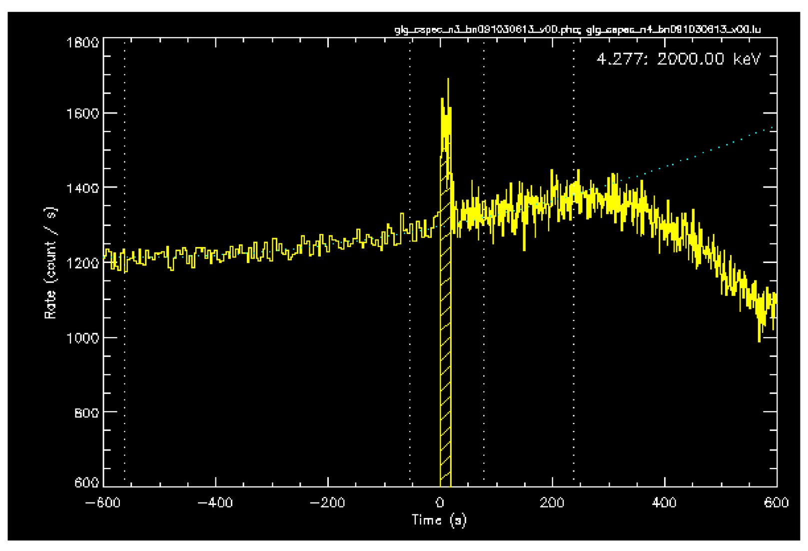

Fig. 1: 3$^{rd}$ NaI detector's background estimation (light blue) and lightcurve (yellow) for the GRB091030 event. The two regions for the fitting are marked by the dotted lines.

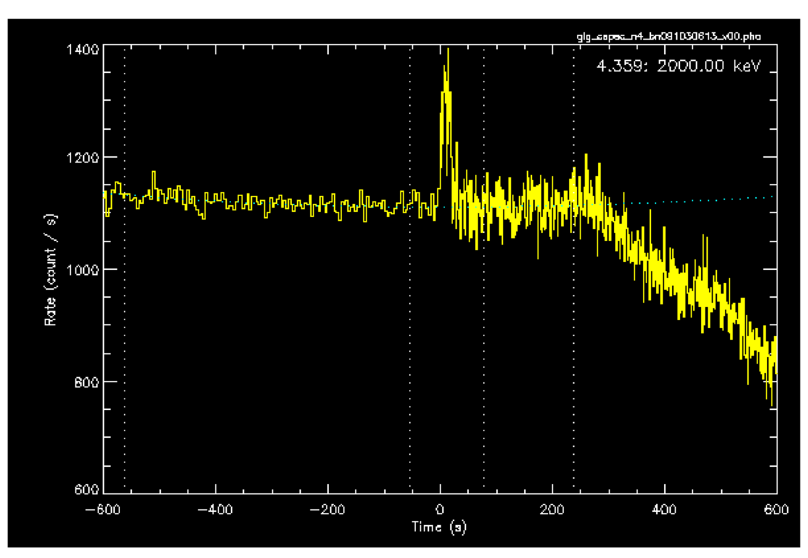

Fig. 2: 4$^{th}$ NaI detector's background estimation (light blue) and lightcurve (yellow) for the GRB091030 event.

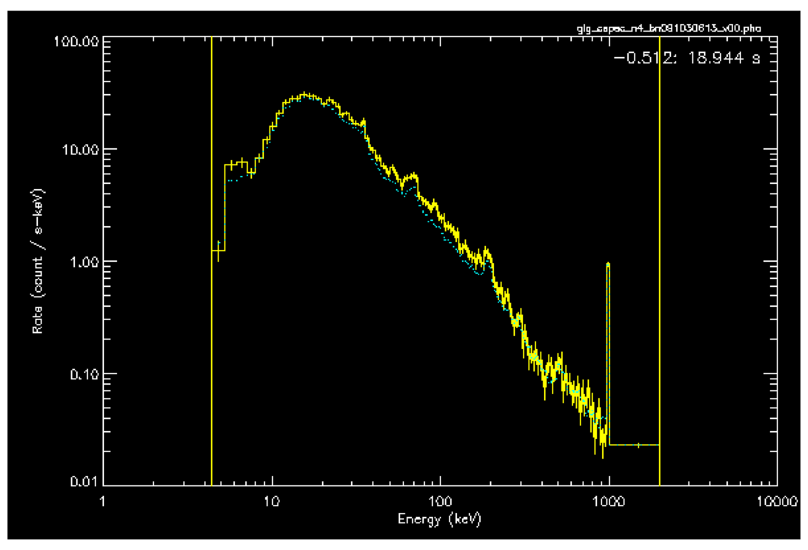

Fig. 3: The energy distribution for GRB091030 event's 4$^{th}$ NaI detector, the background estimation is light blue while the event is yellow.

## Background determination with orbit stacking

The polynomial background estimation is a flexible method, however it does not take into account the physical environment. Fitzpatrick et al. (2012) developed a technique which approximates the background using the data the counts from adjacent days when the satellite was approximately the same geographical position. They are using the fact that the Fermi will be at approximately the same geographical coordinates every 15 orbits, but the satellite's direction is only the same every second orbit, due to the full sky survey. The stacking of the orbital measurements will produce average lightcurves in each energy band for each detectors.

They succesfully used the method for a M2 class solar flare where the orbital background based spectral analysis was consistent with the interpolated approximation's one. The shortcoming of this method is that it is not working during repointing (Autonomous Repoint Request, ARR), triggered by e.g. gammar-ray bursts or other transients. It also suppose that the background is constant during one day (≈ 15 orbits) - e.g. changes in the solar activity or in other sources will be hard to track.

## Background determination with the Direction Dependent Background Fitting

The Direction Dependent Background Fitting (DDBF) method was developed (Szécsi et al. 2012, 2013a,b) for determining the motion effects in the background.
DDBF uses the observed count data and the underlying variables with real physical meaning. The celestial distances of the burst and the detector's orientation, position of the Sun and the Earth are used for the generations of these variables. The background fitting of the GBM lightcurves will be done via multidimensional general least square fitting with Akaike model selection criteria.
The method has many advantages as it can fit long background intervals, removing all the features caused by satellite motion. DDBF fits wuite well the rapidly changing background for a wide time intervall, therefore could be used for long GRBs too.

For the GRB091030 event on Fig. 4 the different detectors' movement is plotted on the sky, Figs. 5-7 show the DDBF fitting for the 3$^{rd}$ NaI detector in several energy ranges.

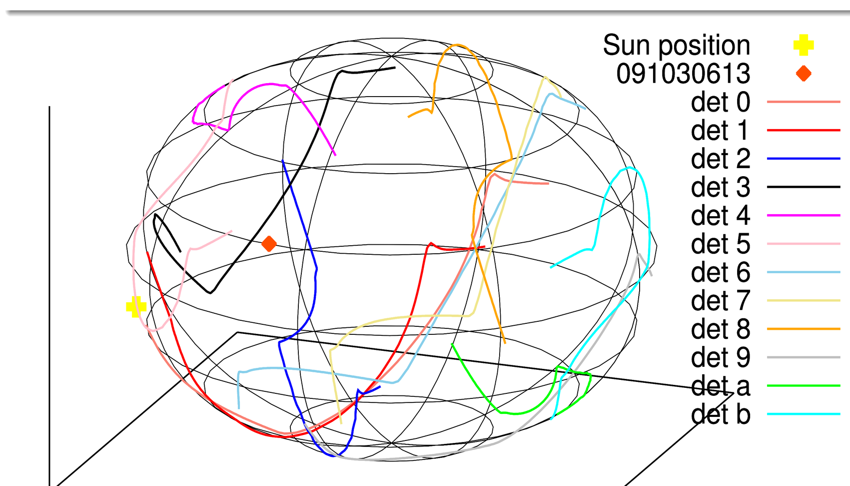


Fig. 4: Direction of the 12 NaI detectors on the sky during the interval around the burst of GRB091030. Sun's position marked with a sphere, the burst position marked with a diamond.

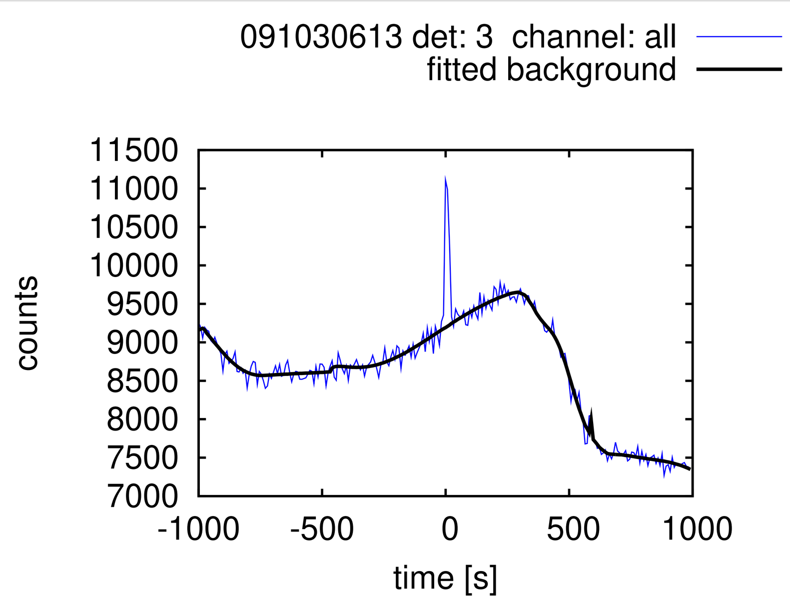


Fig. 5: Result of the DDBF fit, for the 3$^{rd}$ NaI detector's background, in the range of 11.50–982.23 keV.

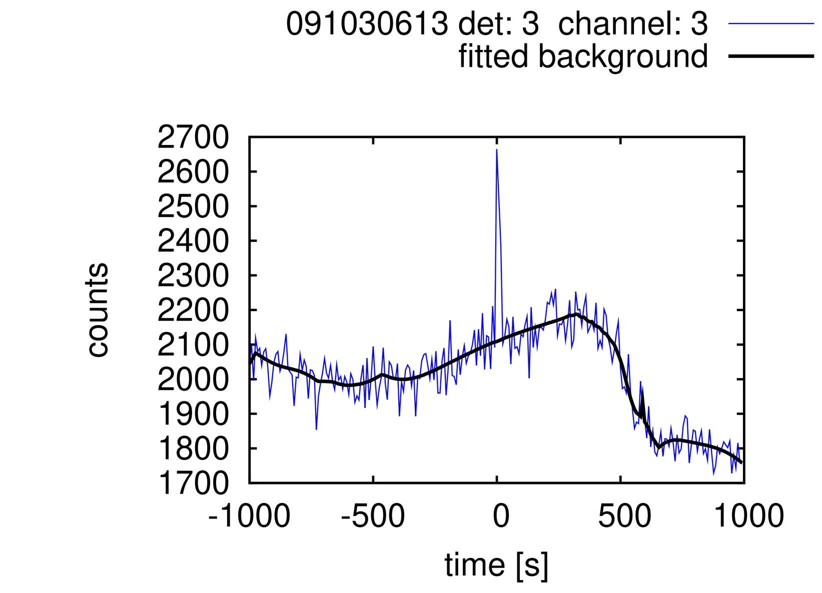


Fig. 6: Result of the DDBF fit, for the 3$^{rd}$ NaI detector's background, in the range of 26.63–50.43 keV.

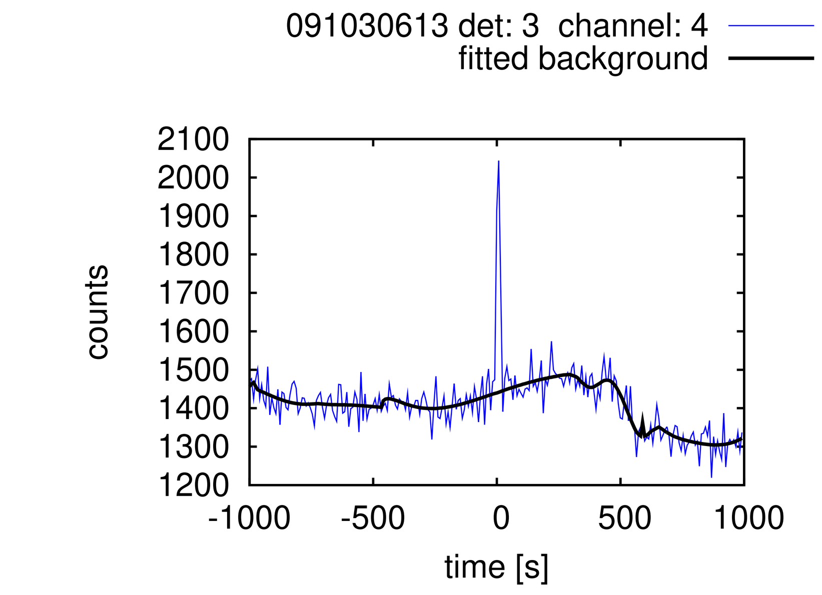


Fig. 7: Result of the DDBF fit, for the 3$^{rd}$ NaI detector's background, in the range of 50.43–102.38 keV.

## Background Components Modelling

Vasileiou (2013) created a tool for the Fermi Large Area Telescope (LAT) background for short-duration observations. The background-estimation tool estimates the highly-variable isotropic background component and the constant-flux Galactic-diffuse emission component, using components such as the Galactic diffuse emission, CR neutral secondaries, background from the geomagnetic position of the spacecraft. These components are estimating the real sources with all the difficulties of the detailed physical modelling, however they estimate the background quite well.

Biltzinger et al. (2020) created a a physically motivated background model for the GBM. It includes the modeling of the different background sources and the DRM response matrix of GBM. The temporally changing responses for point and for extended sources are calculated with the corresponding DRM for every 108 seconds.

The usage of the DRM improves the fit while in the physical background model 6 components were used: constant background, South Atlantic Anomaly, Earth albedo, Cosmic gamma-ray background, cosmic rays, point sources (Crab, Sun). 50 free parameters were fitted for one detector and one channel using MultiNest.
The method clearly superior to the previous `rmfit` estimations as it is capable handling the effects of the Autonomous Repoint Requests and the South Atlantic Anomaly. It could be a problem that the method requires a huge number of free parameters, while to refine the estimations many point sources (some varying) should be taken into account, with the corresponding spectral information.

## Gamma-background estimation with matrix factorization

Neither the DDBF nor the Background Components Modelling could be THE FINAL method for GBM background modelling: optimally any new source or new background component should be automatically included in the process, therefore adaptive-like methods are preferred. The usage of the physical components (or components derived from the observed photon events) are also central: it is clear, that all data of all available detectors and energy channels should be used for the estimation.

In Bagoly et al. (2016) we developed the the Automatized Detector Weight Optimization (ADWO) method for a non-triggered, short-duration transients search. ADWO combines the data of all available detectors and energy channels, identifying those with the strongest signal. With optimized weights to different energy channels and detectors the Signal's Peak to Background's Peak Ratio was maximized in the transient search interval.
The finest GBM resolution is 14 detectors with 128 channels each: if we leave out the 4 lowest and the 2 highest channels (sub-treshold and overflow channels) we get $p = 14 \times 122 = 1708$ channels.
The 2 µs GBM photon event data for each detector and for each channel is quite parse: usually several ms elapses between the photons photons in a given detector and energy channel. It should be somehow binned and spread: a moving average filter with a typical binsize of 512 ms at 1 ms steps will provide high resolution data with correlation. Without filtering, there will be practically no photon-photon correlation in time.
Narrow filters are worthless because of the sparsity constraint, while much wider filters will smooth and filter out the changes. The 512 ms window contains about a few hundreds of photons on typical cases. The filtering will create the $C_{ij}$ light curve in time, $i = 1 \ldots p$ channels and $j = 1 \ldots n$ time bins.

Here we propose to use the matrix factorization with non-negativity constrains to factor the $C$ martrix into two components:

$$C = E \times L$$

, where $E$ is a $p \times j$, $L$ is a $j \times n$ non-negative matrix. The $j$ will give the number of factors: this should be bigger than the number of the real physical components (seen by the detectors with a finite spatial and energy resolution, according to the DRM).

The factorization method is well known in many areas (e.g. Pascual-Montano et al. (2006); Frigyesi & Höglund (2008)) and has the advantage being natural. The $L$ intensity curves are non-negative, just like the real radiation intensity, while the $E$ matrix contains the aggregated count information about the photons' energy.

We imply further constrain for $L$: all rows (component lightcurves) should be fitted with a second order polynomial. Clearly, high order polynomials will produce negative regions where we want to estimate the background. Setting these parts to zero will not help as the approximation breaks down exactly the interpolating region. Rapid changes in the background will require higher $j$ values: as we're looking for background estimation with time regularization overfitting will not be a serious problem. We also normalize the sum of the columns of $E$ to 1.

The algorithms for a matrix factorization with non-negativity constrains exist for almost every computer language: here we use the classic algorithm in Matlab (e.g. Pascual-Montano et al. (2006)), with trivial modifications for the second order $L$ constrain.

We show the GRB091030 background estimation on Fig. 9 .

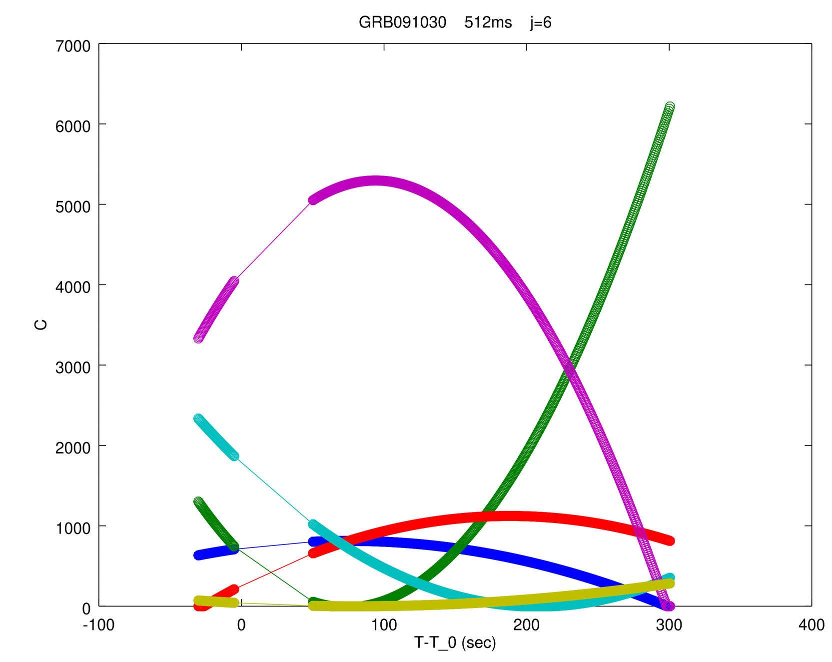


Fig. 8: The $L$ lightcurves for the matrix factorization background estimation of GRB091030. $j = 6$ was used: the yellow component's amplitude is very small altough every component is normalized in energy. The small overall amplitude signals the overfitting.

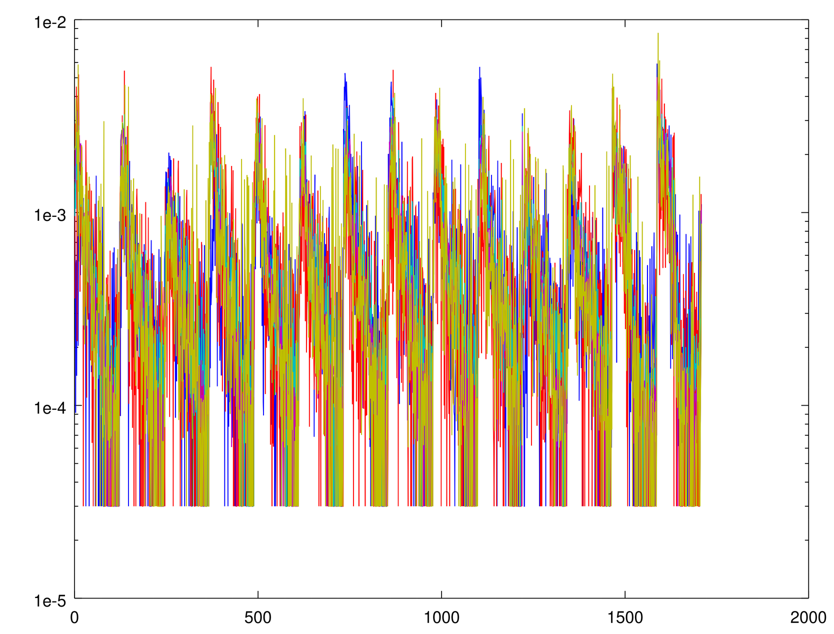

Fig. 9: The $E$ count/energy spectra of the $j = 6$ component. There are $(12+2)$ detectors $\times 128 - 4 - 4 = 1708$ channels. The components' colors are same as on Fig. 9.

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contact: `zsolt.bagoly@elte.hu`
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