The Automatized Detector Weight Optimization (ADWO) method for searching weak electromagnetic counterparts of gravitational waves

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Introduction

We present a new method to search for non-triggered, short-duration transients in the data-set of the *Fermi*'s Gamma-ray Burst Monitor (GBM). The method, called Automatized Detector Weight Optimization (ADWO), combines the data of all available detectors and energy channels, identifying those with the strongest signal. Although it is possible to apply our ADWO method to look for non-triggered short gamma-ray bursts (SGRBs), ADWO works the best if a potential event at a given time. ADWO is ideal to search for electromagnetic (EM) counterparts of gravitational wave (GW) events, when the time of the event is well known from the GW-detectors' observation.

Automatized Detector Weight Optimization

The *Fermi* GBM includes 12 NaI(Tl) and two BGO scintillation detectors.Signals from the photomultipliers are analyzed on-board, and the pulse height analysis converts the peak heights into 128 channels.

Our basic problem is to find the parameters of an event in multi-detector multi-channel time series when the approximate time and direction of the expected signal are given. We give different weights to different energy channels (e_i) and detectors (d_j), and optimize the Signal's Peak to Background's Peak Ratio (SPBPR). These non-negative weights are normalized as $\sum e_i = 1, \sum d_j = 1$.

If the background subtracted intensity in the jth detector's ith energy channel is $C_{ij}(t)$, we define our composite signal as $S(t) = \sum_{i,j} e_i d_j C_{ij}(t)$. The Signal's Peak is the maximum of $S(t)$ within the given time interval, and the Background's Peak is the maximum of $S(t)$ outside this interval. Our goal is to maximize the ratio of these two maximums. The best weights will be built up by iteration, maximizing SPBPR as a function of e_i and d_j. These e_i and d_j weights create an optimal filter among the spectra and detectors. The algorithm will provide not only maximum value of SPBPR, but will search the best weights and the exact time of this maximum, within the pre-defined interval. We applied Matlab's/Octave's *fminsearch* routine to find the maximum. The sample Matlab/Octave code is available on GitHub (`https://github.com/zbagoly/ADWO`).

Analysis of the *Fermi* GBM data

We use CTIME energy channels with limits of 4.4, 12, 27, 50, 100, 290, 540, 980 and 2000 keV ($e_1 \dots e_8$, resp.). Since we look for spectrally hard events, we use only the upper 6 energy channels in the 27-2000 keV range ($e_3 \dots e_8$). The BGO channels start above $\mathbf{100}$ keV, therefore the 27-100 keV energy channels are empty. Overall, we have $\mathbf{6 \times 14 - 2 \times 2 = 80}$ non-zero time series. For each detector and for each channel, the CTTE $\mathbf{2}$ µs event data is filtered with a 64 ms wide moving average filter at 1 ms steps, producing the $C_{ij}(t)$ light curve.

Fermi operates in survey mode most of the time, which creates a continuously changing background. One possibility would be to take the detailed satellite positional information into account and create a physical model to determine the background for a hundreds of seconds (Szécsi et al. 2013). However, we expect that the slow slew will not suppress the sensitivity to the kind of short (~sec) transients. Therefore, a much simpler, 6th order polynomial background fit was subtracted for each channel and detector. We chose the typical background window to be $\approx (\mathbf{-200, 500})$ s.

Table 1: Channel weights

transient	e_3	e_4	e_5	e_6	e_7	e_8
GRB150522B	0.090	0.297	0.315	0.188	0.000	0.110
GW150914	0.203	0.050	0.056	0.559	0.110	0.022
LVT151012	0.260	0.212	0.010	0.113	0.000	0.406

Table 2: Detector weights for the $n0 \dots n9, na$ and nb NaI(Tl) and $b0$ and $b1$ BGO detectors.

transient	$n0$	$n1$	$n2$	$n3$	$n4$	$n5$	$n6$	$n7$	$n8$	$n9$	na	nb	$b0$	$b1$
GRB150522B	0.105	0.106	0.100	0.078	0.146	0.073	0.001	0.031	0.000	0.021	0.009	0.050	0.113	0.167
GW150914	0.000	0.044	0.028	0.151	0.000	0.000	0.035	0.045	0.228	0.090	0.138	0.162	0.000	0.077
LVT151012	0.034	0.062	0.000	0.127	0.073	0.125	0.151	0.000	0.000	0.010	0.234	0.162	0.000	0.022

GRB150522B

To test ADWO, we analyze the short GRB150522B gamma-ray burst: *Fermi* triggered on May 22, 2015 at 22:38:44.068 UTC, and full CTTE data of $(\mathbf{-137, 476})$s interval relative to the trigger is analyzed. The ADWO obtains a maximal SPBPR of 3.12, and reveals the double pulse shown in the *Fermi* GBM quicklook data.

To determine the significance we generated a Poisson-distributed synthetic signal, using the background photon data of the interval, and repeated ADWO for $\mathbf{10^4}$ Monte-Carlo simulations with the same window width. There was no simulation with bigger SPBPR value than 3.12, therefore we estimate the false alarm rate to be below $\mathbf{2 \times 10^{-5}}$ Hz, and the false alarm probability to be below $\mathbf{2 \times 10^{-5}}\,\mathrm{Hz} \times \mathbf{0.125}\,\mathrm{s} \times (\mathbf{1 + ln}(\mathbf{6}\,\mathrm{s}/\mathbf{64}\,\mathrm{ms})) = \mathbf{2.8 \times 10^{-5}}$, analogously to Connaughton et al. (2016).

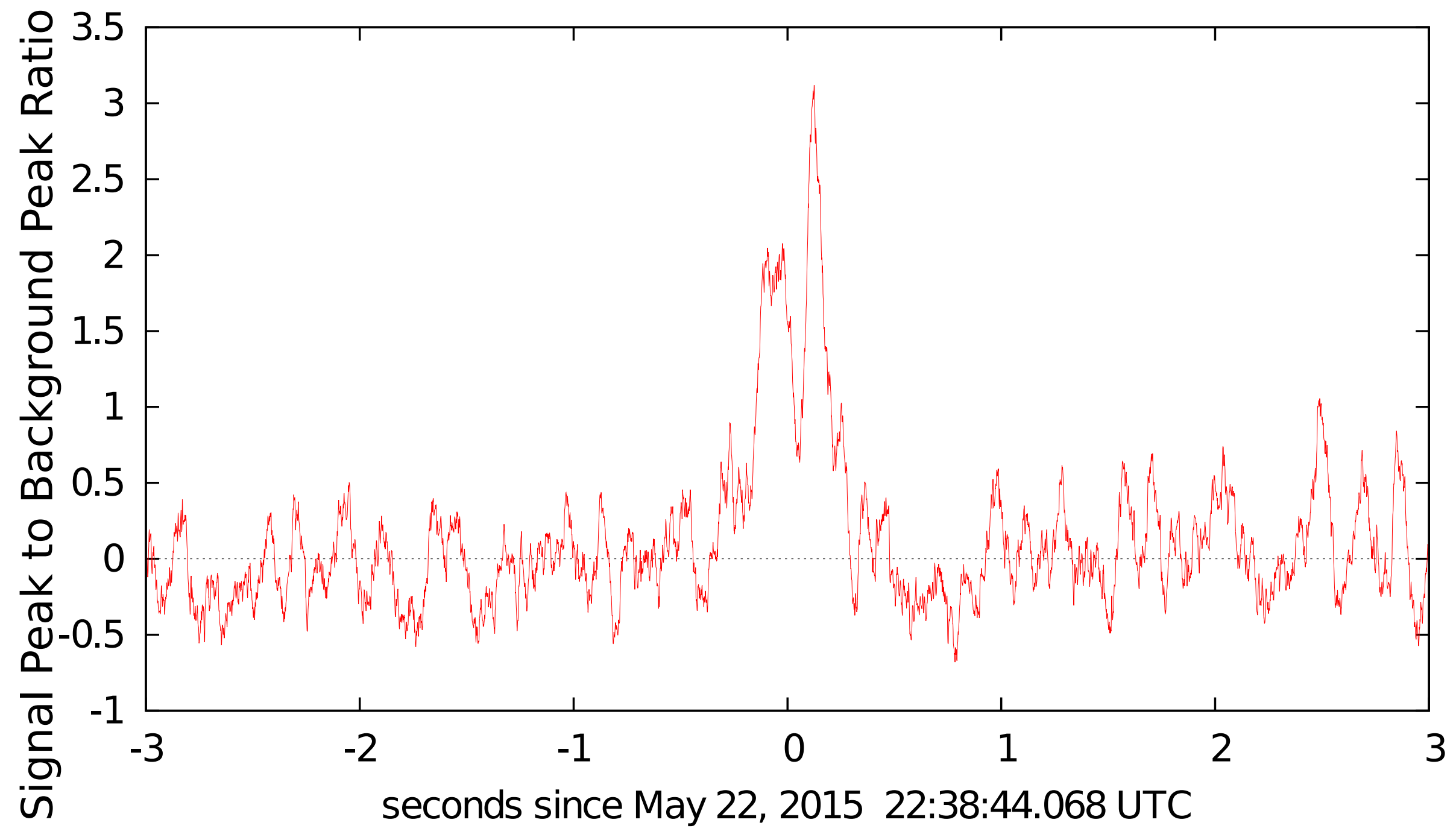

Fig. 1: ADWO light curve of GRB150522B in the 27-2000keV range.

The GW150914 event

On September 14, 2015 at 09:50:45.391 UTC the two detectors of the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal GW150914. GBM observations revealed a weak transient source above 50 keV, 0.4 s after the GW event, with a false alarm probability of 0.0022 (Connaughton et al. 2016).

We apply the ADWO method on the *Fermi* CTTE data set covering the event of GW150914: the 6 s long signal window was centered on September 14, 2015 09:50:45 UTC (391ms before trigger). The ADWO obtained the best SPBPR value of 1.911, 474 ms after the GW trigger. We repeated ADWO for $\mathbf{10^4}$ MC simulations using this data: 86 cases had bigger SPBPR than 1.911. The false alarm rate is $\mathbf{0.0014}$ Hz, giving a false alarm probability of $\mathbf{2.8 \times 10^{-3}}$ Hz $\times$ $\mathbf{0.474}$ s $\times$ $(\mathbf{1 + ln}(\mathbf{6}\,\mathrm{s}/\mathbf{64}\,\mathrm{ms})) = \mathbf{0.0075}$, which is higher than 0.0022, the value given by Connaughton et al. (2016).

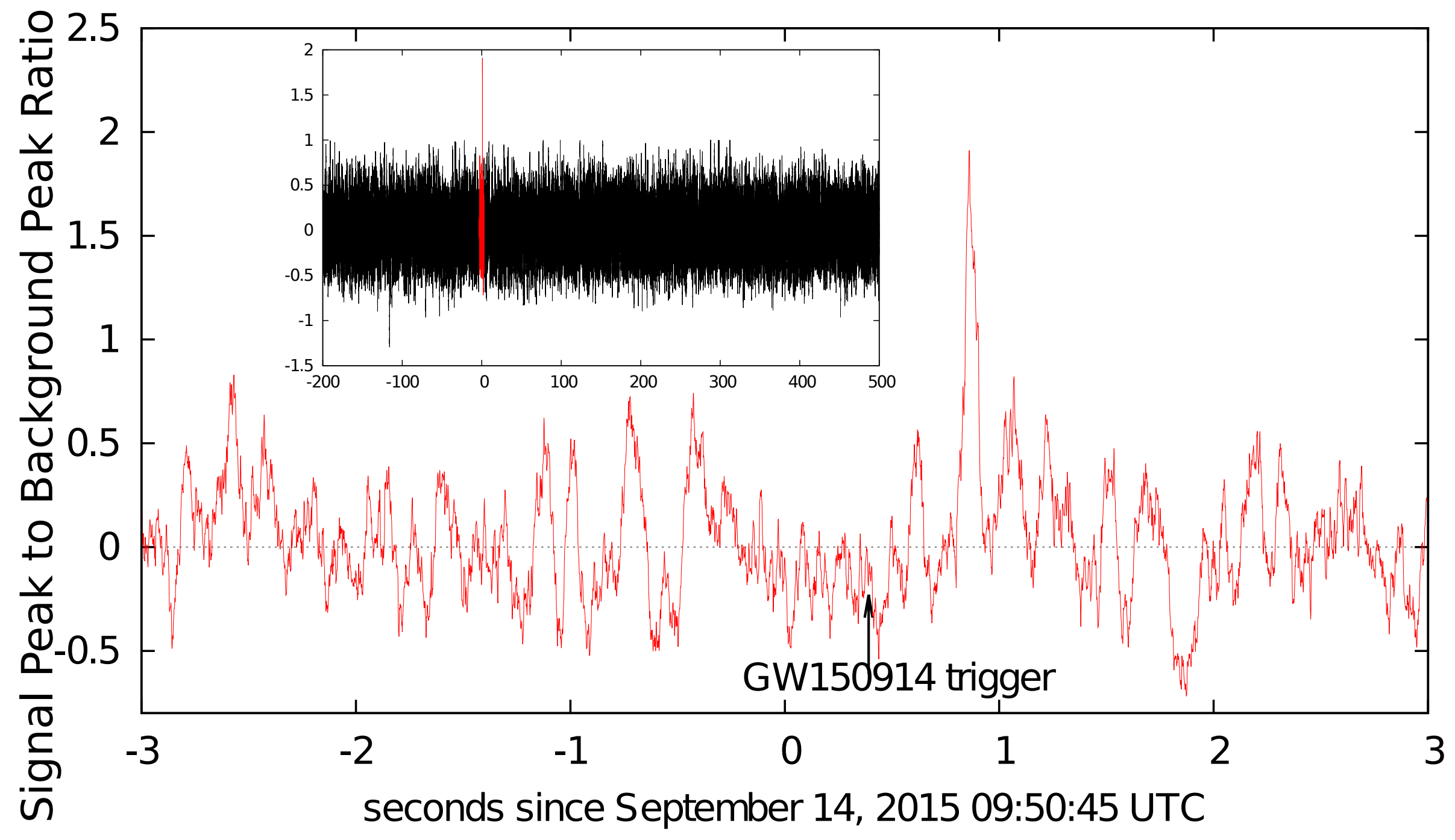

Fig. 2: ADWO light curve of GW150914 in the 27-2000keV range. The inset shows the whole time interval where the ADWO search was performed.

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LVT151012

LVT151012, the second GW candidate transient event occurred on October 12, 2015 at 09:54:43.555 UTC (Abbott et al. 2016; The LIGO Scientific Collaboration et al. 2016). They report a false alarm probability of 0.02, and consider it not to be low enough to confidently claim this event as a real GW signal.

We apply ADWO on the *Fermi* GBM CTTE data around the event of LVT151012, covering $(\mathbf{-195, 495})$ s, centered on October 12, 2015 at 09:54:43 UTC. We find a relatively strong signal at 09:54:44.207 UTC in the 6 s signal window, with a SPBPR of 1.805. The sum of the $\mathbf{27 - 290}$ keV weights is higher than in the case of GW150914, i.e. here the signal is softer than GW150914 at the peak ($E_p \approx \mathbf{3.5}$ MeV), but harder than GRB15522 at the peak ($E_p \approx \mathbf{130}$ keV).

We made $\mathbf{10^4}$ MC simulations: 308 cases had bigger SPBPR than the original observation. hence the false alarm rate is $\mathbf{0.0051}$ Hz, and the false alarm probability is estimated to be $\mathbf{0.01}$ Hz $\times$ $\mathbf{0.652}$ s $\times$ $(\mathbf{1 + ln}(\mathbf{6}\,\mathrm{s}/\mathbf{64}\,\mathrm{ms})) = \mathbf{0.037}$.

When cross-checking the lightning detections made by WWLLN with the *Fermi*'s positions and times, we find no TGF candidates within 500km of the spacecraft position and $\pm\mathbf{900}$ s around the peak.

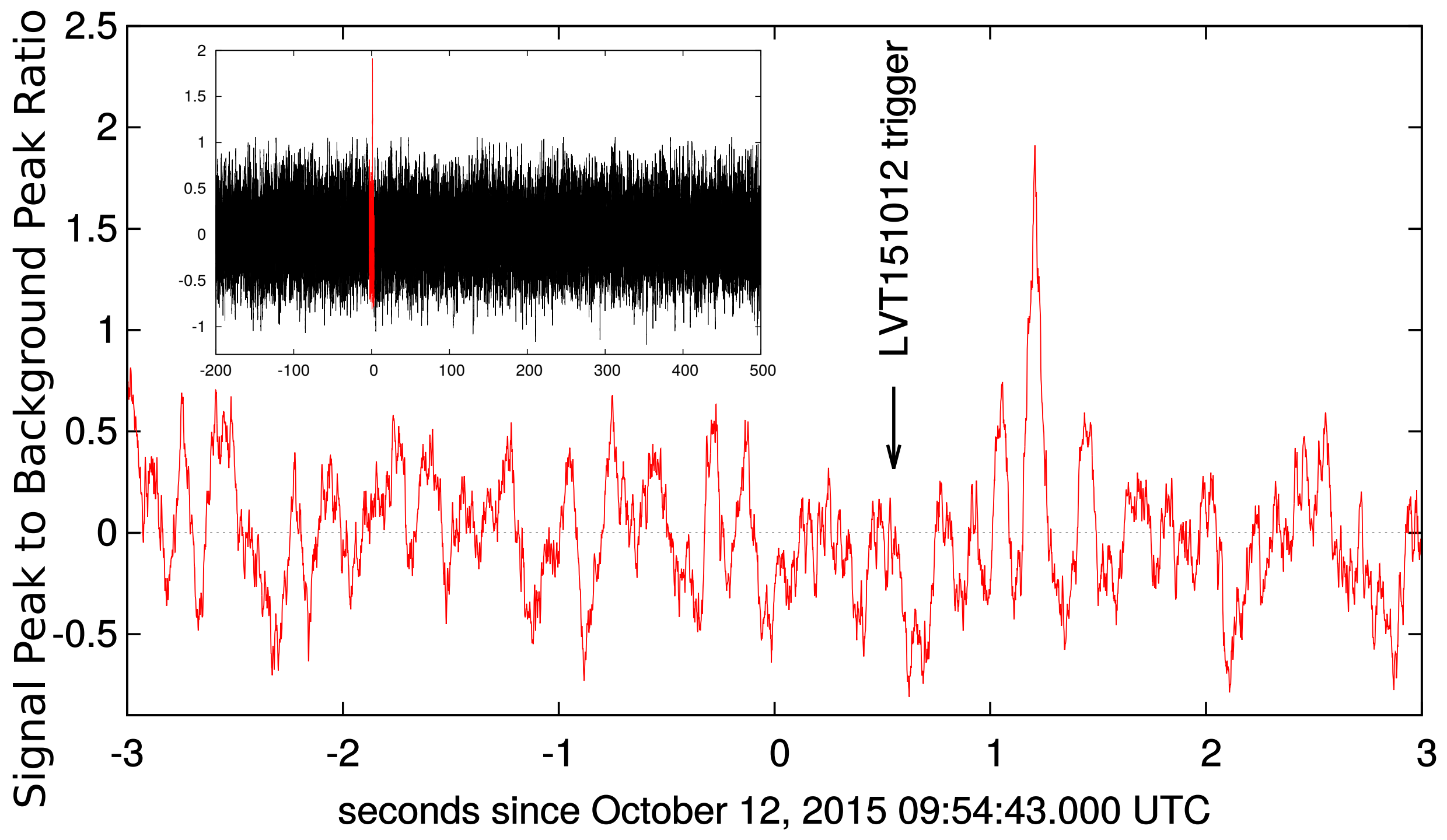

Fig. 3: ADWO light curve of LVT151012 in the 27-2000keV range. The inset shows the whole time interval where the ADWO search was performed.

Discussion

From a theoretical point of view EM counterparts such as short duration GRBs associated with GW events are not excluded. Recently, Perna et al. (2016) proposed a scenario where a double black hole merger is accompanied by a SGRB. The evolution of the system starts with two low-metallicity massive stars that are orbiting around each other (Marchant et al. 2016; Mandel & de Mink 2016). Their orbit is so tight initially that their rotational periods are synchronized with the orbital period. Due to the fast rotation, these stars evolve homogeneously and never expand (Szécsi et al. 2015). This way, the stars avoid the supergiant phase and thus a common envelope evolution, which reduces the theoretical uncertainties involved.

It is likely that there are several potential EM events observed but not triggered. For example, based on the CTIME 256ms data product, Gruber & Fermi/GBM Collaboration (2012) estimates ≈ 1.6 untriggered SGRB/month in the *Fermi* observations. Although here we applied our ADWO method to look for particular events, we point out that it is entirely possible to use this unsupervised data analysis method for a general search for non-triggered, short-duration *Fermi* GBM events.

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