GRB 050915a & the Virgo detector

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Gravitational Waves (GWs) are expected to be emitted in association with Gamma-Ray Bursts (GRBs). In this context, we are analyzing data collected by the Virgo interferometer during 2005 to develop a method aimed to search for coincidences between GW bursts and GRBs. Our analysis is currently focused on Virgo C7 run and the long GRB 050915a, observed by the Swift satellite. The goal of such analysis is either to identify significant events around the GRB trigger time or, in the absence of such events, to set a limit on the strength of the associated GW emission. This study is a prototype for evaluating Virgo capability in constraining the GW output associated with a typical long GRB. Here we give an overview of the procedure we are following in our analysis.

1 Introduction

GRBs are intense flashes of γ-ray photons, lasting from some millisecond to several tens of seconds. Depending on the duration of the prompt γ-ray emission, they have been classified into long bursts, having typically durations greater than 2 s, and short ones, with durations below 2 s. GRBs are isotropically distributed in the sky, they originate at cosmological distances and the isotropic energy output in γ-rays can be as high as 1 $M_{\odot}c^2$. The sudden burst of γ-ray photons is followed by a multi-wavelength (radio-to-X-rays) emission called "afterglow", discovered by the Italian-Dutch satellite BeppoSAX in 1997 [1]. The discovery of long GRB afterglows opened the way to redshift measurements [2], that have definitely confirmed the cosmological origin of these events. A similar major advance in GRB research was recently provided by the NASA's *Swift* satellite, that, among other important results, has succeeded in localizing short GRB afterglows [3].

Currently, the most favored scenario relates short and long GRBs to different types of progenitors (see e.g. [4] and references therein): long GRBs are thought to be produced by massive stars during the explosions of their cores (so-called "collapsar" scenario), while short ones are believed to originate in compact binary mergers (such as Neutron Star (NS)-NS or Black Hole (BH)-NS mergers). In order to power a GRB, it is required that the progenitor stellar system evolves ending in the formation of a BH plus accretion disk, whose accretion onto the BH releases the energy necessary to power an ultra-relativistic flow, called "fireball". Dissipation of the fireball kinetic energy, via shocks originating at distances larger than $\sim 10^{13}$ cm from the central source, explains the observed radiation. Due to the large distance, the central engine powering the GRB is in fact hidden from direct observation in the electromagnetic window. However, a direct signature of its identity may come from the gravitational window, since GWs should be produced in the immediate neighborhood of the source, after the catastrophic stellar explosion.

2 GBR 050915a and Virgo C7 run

In the context of the possible association between GRBs and GWs, we have started a work on GRB triggered searches for GW signals using the Virgo detector [5]. A similar triggered search was performed by LIGO during its second science run, in coincidence with GRB 030329[6]. Virgo is an Italian-French experiment [7]. Jointly funded by INFN (Italy) and CNRS (France), it is located at the European Gravitational Observatory (EGO), near Pisa. Virgo is an interferometric device dedicated to detection of GWs. More specifically, it is a power recycled Michelson interferometer, with 3 km long arms. GWs result in a shift of the interference pattern produced by the interferometer, and thus in a change on the amount of light that is collected as its output. A recent review of Virgo status is given by [8].

At the time of GRB 050915a, Virgo was engaged in a 5-day long data run, named C7. The "Burst Alert Telescope" (BAT) on-board *Swift* was triggered by GRB 050915a on the 15th of September 2005, at T$= 11:22:42$ UT. The BAT on-board calculated position for this burst was RA=05h 26m 51s, Dec=-28d 01$'$ 48$''$ (J2000), with an uncertainty of 3 arcmin. GRB 050915a had a γ-ray ($15-350$ keV) duration of (T_{90}) 53 ± 3 s, making it a long-type GRB. The "X-ray Telescope" (XRT) began observing GRB 050915a at $11:24:09$ UT (~ 87 s after the trigger). The new refined position was RA=05h 26m 44.6s, DEC=-28d 01m 01.0s [10].

During C7 run, Virgo sensitivity exceeded that of any previous run. The lowest strain noise was of $\sim 6 \times 10^{-22}$ Hz$^{-1/2}$, around ~ 300 Hz. We have thus started performing an analysis of Virgo data simultaneous with the long GRB 050915a, aimed to search for a burst-type GW signal associated with this GRB. The redshift of this burst is not known, but considering that long GRBs in the *Swift* sample have typically $z > 2$ [11], and taking into account current theoretical estimates for the GW emission by the most likely GRB progenitors (e.g. [12]), we expect the searched signal in the Virgo detector to be very weak. In the absence of significant events, the aim of our analysis is to set an upper-limit on the signal strength.

3 Pipeline overview

For our analysis, we relied on a single lock stretch (about 16845 s of data), containing the GRB trigger time. A part from a time window 300 s long centered on the GRB trigger time, data within this lock stretch are used as "background", i.e. they are used to determine the false alarm rate and set a reasonable threshold for "good" events, to use when scanning the "signal region". The last is defined as a data segment 180 s long, 120 s before the GRB trigger time and 60 s after. Together with 60 s of data before its start and after its end, this data segment makes up the 300 s of the stretch which are not included in the background region. A 180 s duration for the signal region (roughly ten times the GRB duration) is chosen so to cover most of astrophysical predictions regarding the expected delay between the GRB and the associated burst-type GW signal.

To search for burst-like events, we run the "Wavelet Detection Filter" (WDF, see [13,14]) on both the background and signal region. The output of this filter is a list of events, each characterized by a time, a duration and a signal-to-noise ratio (SNR, i.e. the event strength). For our analysis, only events having a SNR greater than 4 are considered. The filter has a time resolution of 0.6 ms, that is the duration of a single temporal bin. If the SNR is above threshold (SNR=4) in two consecutive bins, and if the time delay between those two bins is less than a given time interval called clusterization window (set to 10 ms in our analysis), then the bins are considered as part of the same event. In this way, we can associate to each event a time duration, given by the time difference between the first and last bin found to be part of the same event. Among the bins recognized as part of the same event, the time of the one at which the SNR reaches its maximum, sets the event time.

By running the WDF filter on the background region, we construct the distribution of false alarm rate as a function of the event strength threshold and determine our good events threshold, i.e. the SNR threshold needed to have an expected rate of false alarms of 5×10^{-4} Hz. A threshold of this kind, applied in a time window 180 s long (the duration of our signal region), corresponds to a $\sim 10\%$ chance (assuming Poisson statistics) of finding a false coincidence with the GRB trigger. When scanning the signal region in search for a GW burst coincident with the GRB, we thus discard all events with SNR lower than this threshold, that in our case turns out to be SNR=26.

After selecting our good events threshold, we calibrated our pipeline for different kind of waveforms by using software injections. Given the still large uncertainties in the predictions for GW signal waveforms expected to be associated with a long GRB, we have performed an analysis aimed to the detection of quite general types of GW bursts, like sine-Gaussians, Gaussians and damped sinusoids. Typical durations of the injected signals are in the range $1-100$ ms, with frequencies between 203 Hz and 1503 Hz. The calibration procedure consists in two steps: first, we characterize the filter efficiency in detecting signals at specific frequencies and with specific durations, as a function of their strength; then, we define a conversion factor between the detected event strength (SNR) and true event strength, that we quantify in terms of the signal "root-sum-square" amplitude, $h_{rss} = \int_{-\infty}^{+\infty} |h(t)|^2 \, dt$.

Once concluded the calibration procedure on the background region, we scan the signal region with the WDF filter and search for events above our good events threshold of SNR=26. We find that in the source region there are no events with strength greater than this threshold, so a coincident search is prevented and we are going toward the definition of an upper-limit strain amplitude. For each type of injected burst signal, our upper-limit strain amplitude will correspond to the h_{rss} value giving a detected SNR of 26

4 Conclusions

We have presented an overview of the analysis that is being performed on Virgo data taken during the 2005 run named C7. Our work is aimed to search for a burst of GWs associated with the long GRB 050915a, that was detected by the *Swift* satellite when Virgo was taking data in science mode. This is the first time an analysis of this kind is being performed using the Virgo detector, thus its importance is crucial for establishing the level at which Virgo is actually able to constrain the GW output from GRB sources, but also as a prototype for future similar analysis, that will be carried with improved sensitivity.

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