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Correlation between gamma ray bursts and gravitational wave bursts: the AURIGA complete data analysis

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Abstract
A widely accepted paradigm for astrophysical models of gamma ray bursts (GRB) prescribes a compact 'central engine' dominated by gravitational interactions, and therefore a concurrent emission of GRBs and gravitational wave bursts is likely to occur. Consequently, we have tested a novel and reliable method for searching for time correlation in the AURIGA and BATSE complete dataset. The analysis covers the period 1997–1999. The obtained upper limit on the averaged gravitational wave energy released in a neighbourhood of 300 s around the GRB triggers is $h_{\mathrm{RMS}} = 1.8 \times 10^{-18}$ at 95% confidence level. We also estimate the minimum statistical coverage of confidence levels for a frequentist interpretation of our upper limit.

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1. Introduction

Flashes of γ radiation, known as gamma ray bursts (GRB), light up the sky with a mean rate of one per day. The cosmological origin of GRBs is widely accepted: the data collected using the BATSE satellite have demonstrated that GRBs are isotropically, but not homogeneously, distributed over the sky [1], as confirmed by the BeppoSAX satellite observations [2]. The occurrence of gravitational wave bursts (GWBs) associated with GRBs is a natural consequence of current models for the central engine [3]. For instance, GRBs can be produced by a class of supernovae, known as collapsar or hypernovae, when a massive star collapses to form a spinning black hole; in the meantime the remaining core materials form an accreting torus with high angular momentum [4, 5]. Another interesting scenario is a neutron star and black hole ($\sim 7M_{\odot}$) coalescing system where the disruption of the neutron star, caused by the rapidly rotating black hole, will also form a torus emitting a large amount of energy ($\sim 0.1 M_\odot c^2$) both in gravitational and electromagnetic waves [4]. For the GWB models, the amplitude of the gravitational wave strain is expected to be $h \sim 10^{-23}$–10^{-21} at cosmological distances, i.e. $\sim$1–3 orders of magnitude greater than the sensitivity of planned ground-based gw detectors. These commonly accepted estimates require search methods able to cumulate the GWB effects, for instance, by exploiting their time correlation with detected GRBs.

The aim of this paper is to present a reliable method to find a GWB versus GRB time correlation and to complete the previous analysis [6]. From the experimental runs performed during the years 1997 and 1998 the AURIGA detector exhibited a sensitivity level of $h_{\min} \approx$ 2–8 $\times 10^{-19}$, where $h_{\min}$ is the minimum gw amplitude detectable with unitary signal-to-noise ratio (SNR) [7]. In 1999, the sensitivity was improved by a factor of two using a better room temperature amplifier. The overall duty cycle was $\sim 1/3$ of the total observation time (1997–1999). It is worth noting that AURIGA, as any other resonant detector, is quite insensitive to the details of GWB waveforms. This is related to its narrow detection band, typically 1 Hz around the two resonance frequencies (913 and 931 Hz) of the bar and transducer system. As a consequence, 'blind' searches for GWBs over an event list produced by a resonant gw detector have a poor signature in the low SNR regime [8–10]. However, such a drawback of narrow-band detectors is somewhat compensated when the gw search is focused on specific time spans around GRB triggers: in fact, as we will show in section 2, the total gw energy released in the detector is relevant for a search triggered by electromagnetic emission, and GWB waveforms can be safely treated as a δ-like pulse.

There are two main sources of uncertainties in correlation searches with γ-triggers which greatly affect their overall sensitivity: (i) the delay T_{gw} between a GWB and the corresponding GRB; (ii) the selection of GRBs suitable for correlation searches with a gw detector. In this paper, we have considered almost constant delays, i.e. the delay jitter is assumed to be less than the inverse of the AURIGA bandwidth ($\sim$1–2 s). As far as the selection of GRB triggers is concerned, we have taken into account all triggers collected in the BATSE catalogue falling into validated time spans of the AURIGA detector.

The crucial problems addressed in this paper are related to the background estimation in the presence of a non-stationary noise and the evaluation of the upper limits characterized by a minimum statistical coverage of the corresponding confidence interval. In fact, the operation of the AURIGA detector over a long time period (3 years) showed a strong non-stationary behaviour of the noise variance. Moreover, a lot of spurious events with a non-uniform rate originating from unmodelled noise sources [9] appeared in the detector output. In this framework, the detection statistics and the corresponding confidence intervals have to be estimated by Monte Carlo methods, i.e. by injecting a large number of impulsive signals into the real AURIGA noise; the event amplitudes are drawn from astrophysical distributions characterized by different averaged gw energy.

The paper is organized as follows. In section 2, we summarize our improved method of statistical search for a GWB–GRB time correlation and also we present the new features devised for the analysis. In section 3, we present our results and the relevance of some assumptions on the AURIGA data with the help of Monte Carlo methods. Discussion and conclusions follow, respectively, in sections 4 and 5.

2. Search method

The non-stationarities of the detector noises and the uncertainties on delay T_{gw} between γ and gravitational bursts led us to elaborate on a reliable statistical method for searching for GWB versus GRB time correlations. Our method has been demonstrated to be quite insensitive to the above issues. In order to gain in sensitivity, it requires a 'reasonable' assumption on expected delays, i.e. the standard deviation $\sigma_{T_{gw}}$ of delay fluctuations around the mean value (delay jitter) should not exceed the inverse of the detector bandwidth, namely 1–3 s for the AURIGA detector. In contrast, the mean delay $\langle T_{gw} \rangle$, where $\langle \cdot \rangle$ represents the average over the astrophysical population of the GRBs, is left unconstrained.

The proposed statistical method relies on the observation that, if there is a concurring emission of GWB and GRB, the output of the gw detector at GRB arrival time, properly shifted by the T_{gw} delay, should be, on average, more energetic than the output at other times. Stated differently, the statistical behaviour of the detector's output is modified by the presence of GWBs. In the following we adopt a discrete time domain representation: we substitute for the continuous noise $n(t)$ and signal $h(t)$ a finite length sequence of samples $n_i \equiv n(t_i)$ and $h_i \equiv h(t_i)$, respectively; here $t_{i+1} - t_i \equiv \Delta t$ is the sampling time, which corresponds to 14.336 ms for the AURIGA filtered output. The energy of the filtered output, within a time window $2W = 2N\Delta t$ centred at the GRB trigger t_α, is represented by the statistical variable $X(t_\alpha)$ defined as

$$X(t_\alpha) = \frac{1}{2N} \sum_i f_i^2, \tag{1}$$

where $f_i = hu_i + n_i$ is the sampled output of the Wiener filter matched to a δ-like signal [11]. A well-known result of the Wiener filtering theory is that the response of the filter to its matched signal and the auto-correlation of the filtered noise are proportional to the same function u_i. Note that this result reflects the time invariance of the stochastic process $n(t)$, which is approximately met by quasi-stationary systems. Quasi-stationary behaviour has been observed in the real noise of the AURIGA detector on a time scale of at least several hours [11]. For a narrow-band detector and for a wide class of impulsive waveforms, u_i turns out to be a superposition of two exponentially damped oscillating functions with nearby frequencies. A convenient approximation for u_i is [9]

$$u_i \simeq \exp[-|\mathrm{i}|/\hat{\tau}_w] \cos(\hat{\omega}\mathrm{i}) \cos(\hat{\Omega}\mathrm{i}), \tag{2}$$

where $\hat{\tau}_w \equiv \tau_w/\Delta t$, $\hat{\omega} \equiv \omega\Delta t$ and $\hat{\Omega} \equiv \Omega\Delta t$ are the dimensionless Wiener filter decaying time τ_w, carrier frequency ω and amplitude modulation frequency Ω.

The statistical variable $X(t_\alpha)$ depends very weakly on noise correlation parameters τ_w, ω and Ω. It depends, otherwise, on the local noise variance and, for the window centred on the correct delay, on the amplitude signal h. In principle, the $X(t_\alpha)$ belong to two complementary statistical populations: (i) the on-source population χ_{on}, when W contains the GWB or (ii) the off-source population χ_{off}, corresponding to windows that leave out any GRB. The sets χ_{on} and χ_{off} have probability distributions p_{on} and p_{off}, respectively.

Depending on the window W we have

$$X_{\mathrm{off}} = \frac{1}{2N} \sum_i n_i^2 = \sigma^2 \tag{3}$$

$$X_{\mathrm{on}} = \frac{1}{2N} \sum_i (hu_i)^2 + X_{\mathrm{off}} = \frac{\tau_w}{2W} \frac{h^2}{4} G_{\mathrm{on}}(\tau_w, \omega, \Omega) + X_{\mathrm{off}}, \tag{4}$$

where the cross term $\sum_{i=-N}^{N} hu_i n_i$ has been neglected as the noise has zero mean. The function

$$G_{\mathrm{on}}(\tau_w, \omega, \Omega) = 1 + \frac{1}{1 + \tau_w^2\omega^2} + \frac{1}{1 + \tau_w^2\Omega^2} + \frac{1}{2}\left[\frac{1}{1 + \tau_w^2(\omega - \Omega)^2} + \frac{1}{1 + \tau_w^2(\omega + \Omega)^2}\right] \tag{5}$$

is close to unity for typical values of the AURIGA detector parameters. For instance, allowing the maximum fluctuation of measured parameters during the 3 year run, i.e. $0.2 \lesssim \tau_w \lesssim 1.6$ s, $919 \lesssim \omega/(2\pi) \lesssim 921$ Hz, $8 \lesssim \Omega/(2\pi) \lesssim 10$ Hz, we have $1 \lesssim G_{\mathsf{on}} \lesssim 1.01$.

In order to test the hypothesis of the existence of a GRB versus GWB time correlation, we use the Mann–Whitney test, also known as the rank sum test or U-test [12]. The Mann–Whitney test does not assume that the two populations off and on follow Gaussian distributions but it does assume that the two samples are randomly and independently drawn. Accordingly, the Mann–Whitney test is useful for systems plagued by non-modelled backgrounds and/or quasi-stationary noises, as an unbiased reference set for the off population can be constructed.

The U-test works by ranking all the elements of the union set $\chi_{\mathsf{off}} \oplus \chi_{\mathsf{on}}$ ordered by increasing values, and adding the rank of each element to the parent set: $R_{\mathsf{off}} = \sum R(X_{\mathsf{off}})$ and $R_{\mathsf{on}} = \sum R(X_{\mathsf{on}})$. The value of the statistical variable U is defined by the following relations:

$$U = (R_{\mathsf{on}} - \mu_{\mathsf{on}})/\sigma_U \tag{6}$$

$$\sigma_U^2 = N_{\mathsf{off}} N_{\mathsf{on}} (N_{\mathsf{off}} + N_{\mathsf{on}} + 1)/12 \tag{7}$$

$$\mu_{\mathsf{on}} = N_{\mathsf{on}} (N_{\mathsf{off}} + N_{\mathsf{on}} + 1)/2. \tag{8}$$

We take advantage of the classical theory of *hypothesis testing* to establish if the GWBs impinging on the detector affect the statistical characteristic of its output, i.e. the on probability distribution. The null hypothesis $\mathcal{H}_0$ that the two populations off and on are identical and the alternative hypothesis that they differ only in their mean value, can be stated as $U < U_{\mathrm{cr}}(\varepsilon)$ and $U \geqslant U_{\mathrm{cr}}(\varepsilon)$, respectively, where $U_{\mathrm{cr}}(\varepsilon)$ is the critical value of U at a given confidence level $1-\varepsilon$ and ε is the statistical significance of the test. The rejection of the $\mathcal{H}_0$ hypothesis supports an association between GRBs and GWBs. In such a case, the difference of the mean values of the off and on populations is proportional to the squared GWB amplitude $h^2_{\mathsf{RMS}} \equiv \langle h^2 \rangle$, where the average is taken over the GWB source population.

If the requirements of the Mann–Whitney test are met, the one-tailed z-test [13] can be applied to its outcome U. In the next section we will discuss how to carefully check this crucial statement by means of Monte Carlo runs.

Now, we address the question how to set upper limits with minimum statistical coverage, taking into account the physical boundaries $X_{\mathsf{on}} \geqslant 0$ and $h_{\mathsf{RMS}} \geqslant 0$. Note that the calculation of a confidence level is trivial only for Gaussian variates without physical constraints. After the estimation of the experimental background (X_{off} probability distribution) and the choice of the nominal confidence level $1 - \varepsilon$, we define the confidence interval of the measured quantity h_{RMS} to be in the range $h_{\mathrm{inf}} < h_{\mathsf{RMS}} < h_{\mathrm{sup}}$. To compute these limits we have to relate the outcomes of the U-test to the physical parameter h_{RMS}. This can be achieved by means of Monte Carlo simulations. We indicate with h_U the nominal h_{RMS} connected to the U and with $p(h_U)$ the corresponding probability distribution. If the null hypothesis $\mathcal{H}_0$ is true, the boundaries of the confidence belt are set to $h_{\mathrm{inf}} = 0$ and $h^2_{\mathrm{sup}} = h^2_U + \delta h^2$; in the opposite case we have $h^2_{\mathrm{inf}} = h^2_U - \delta h^2$ and $h^2_{\mathrm{sup}} = h^2_U + \delta h^2$, where

$$\delta h^2 = \frac{P^{-1}(1-\varepsilon)}{\sqrt{2}} \sigma_{\mathsf{off}} \tag{9}$$

and $P^{-1}(x)$ is the quantile of the underlying distribution $p(h_U)$, i.e. the inverse of its cumulative distribution $P(x) \equiv \int_0^x p(x)\,\mathrm{d}x$. This procedure defines a confidence belt for the measured background with a statistical coverage greater or equal to the confidence level $1 - \varepsilon$ [13].

For the sake of clarity, we have classified into three groups (see table 1) the relevant parameters of our search method, depending on their physical meaning and relevance:

Table 1. Parameters entering the GRB–GWB time correlation search.

Detector noise	τ_w, ω, Ω, σ
Statistical	ε, N_{off}, N_{on}, W
Averaged GWB signal	h_{RMS}

(i) characterization of the detector noise (correlation function and noise level); (ii) statistical parameters; (iii) gw signal amplitude, averaged over the GWB source population.

The search method has been debugged through complete simulations of both the detector noise and gw signals. The numerical algorithms have been thoroughly tested letting the parameters listed in table 1 be unbounded. The method has been applied to real data, by varying only ε, N_{off} and W in different Monte Carlo runs. One of the most appealing aspects of the above outlined method is the complete scalability of both the physical and the statistical parameters, which makes it directly applicable to gw detectors, either resonant or interferometric, with different sensitivities and bandwidths.

3. Results

The AURIGA dataset used in the present analysis is relative to the years 1997–1999 and to GRB triggers retrieved from the BATSE catalogue [1]. The selected γ-triggers have been associated with the AURIGA data stretch falling into validated time spans. The data validation procedure used for the IGEC analysis has been the same [8, 10]. This procedure tests the separability of the events rising above the noise level and the Gaussianity of the detector output once the events have been subtracted. This remarkably reduces the AURIGA duty cycle and the number of GRBs available for the correlation analysis reduces to about ~200 in three years of data taking. We have shown that the AURIGA data within these time spans can be locally modelled as a quasi-stationary Gaussian process [9]. Unfortunately, the variation of the detector environment (seismic noise, level of electromagnetic interferences, stability of the cryogenic point, etc) made the noise highly non-stationary over the total run, as clearly shown in figure 1, which reports the mean squared noise of the Wiener filtered output. As pointed out by the IGEC analysis [8, 10], the correlation search is affected by the presence, even in the validated data, of background events with non-homogeneous rate (ranging from 100 to 400 events per day). Small background events give rise to the long tail in figure 1. The occurrence of large (spurious) background events in concomitance with 11 GRB triggers has been handled by excluding these GRBs from the present analysis.

3.1. Monte Carlo simulations

The Monte Carlo simulations of the AURIGA noise with superimposed GRB signals are useful to test the search method under several working conditions and to study the dependence of U on the window value. The parameters, τ_w, ω and Ω, have been kept close to the real ones. The nominal confidence level for the calculation of the U critical value has been fixed at $1 - \varepsilon = 0.95$.

A run of Monte Carlo simulation consists of four steps: (i) choice of a p_{off} probability distribution with a given mean μ_{off} and standard deviation σ_{off}; (ii) build-up of the χ_{off} set with N_{off} elements using standard discrete distribution algorithms; (iii) addition of incoming signals to form the on set χ_{on} (see equations (3) and (4)); (iv) computation of the U statistical variable. It is worth noting that the gw signal affects the on population with its mean squared value h^2_{RMS} and that, due to statistical fluctuations, the sample variance σ differs from the standard deviation σ_{off} of the off distribution.

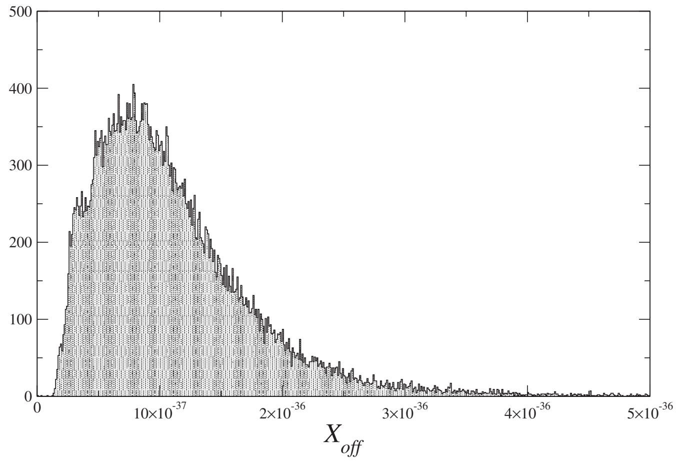

Figure 1. Distribution of the AURIGA off data. The width of the time window is $W = 3$ s, starting from 1 h before the GRB trigger to 1 h after, skipping 10 min around each trigger.

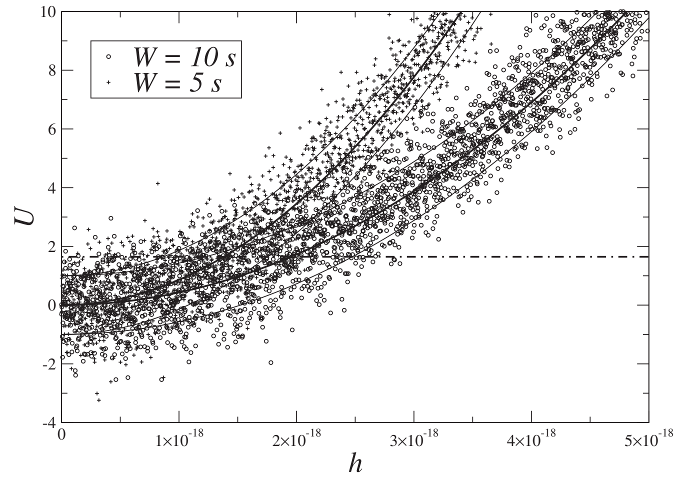

Figure 2. Values of the U statistical variate obtained in Monte Carlo simulations, using two different values of the time window amplitude, with $N_{\mathsf{off}} = 5000$ and $N_{\mathsf{on}} = 2000$. The continuous line represents the theoretical mean value of U (see equation (10)), and the one standard deviation range from it. The dashed-dotted line $U \simeq 1.645$ represents the critical value for $1 - \varepsilon = 0.95$.

The effectiveness of the method is shown in figure 2, where the U outcomes obtained with increasing values of h^2_{RMS} are plotted. From a thorough inspection of the Monte Carlo result we can conclude that the U statistical variable has the same distribution as Student's t (which holds for the normal distribution) with mean

$$\langle U \rangle = \frac{1}{4}\frac{\tau_w}{2W}\frac{h^2_{\mathsf{RMS}}}{\sigma_{\mathsf{off}}}\sqrt{\frac{N_{\mathsf{off}}N_{\mathsf{on}}}{N_{\mathsf{off}} + N_{\mathsf{on}}}}G_{\mathsf{on}}(\tau_w, \omega, \Omega) \qquad (10)$$

and unitary standard deviation. This result, which gives the sensitivity of the above described procedure, is not a straightforward consequence of the central limit theorem as the p_{off} probability for the AURIGA detector is clearly non-Gaussian. The agreement of the Monte Carlo simulations with equation (10) is the main result of this paper and confirms,

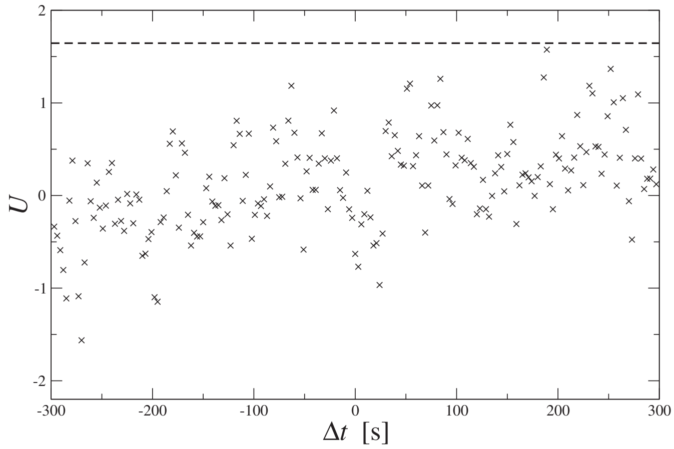

Figure 3. Search applied to the AURIGA data, with $W = 3$ s and shift ΔT_{gw} from -300 to 300 s with steps of 3 s, $N_{\mathsf{off}} = 47\,000$, $N_{\mathsf{on}} \simeq 190$ (it depends on the shift value because of the vetoes). The dashed line at $U = U_{\mathrm{cr}} \simeq 1.645$ represents the critical value for $1 - \varepsilon = 0.95$.

a posteriori, the upper limit of our previous work [6], where we approximated the bulk parts of the on and off probability distributions with the normal distribution.

In the absence of statistical evidence for time correlations between GRBs and GWBs, we can estimate from equation (10) the minimal signal amplitude h_{crRMS} for a given statistical significance:

$$h^2_{\mathsf{crRMS}} \leqslant U_{\mathrm{cr}} \frac{4\sigma_{\mathsf{off}}}{G_{\mathsf{on}}(\tau_w, \omega, \Omega)} \frac{2W}{\tau_w} \sqrt{\frac{N_{\mathsf{off}} + N_{\mathsf{on}}}{N_{\mathsf{off}} N_{\mathsf{on}}}}, \tag{11}$$

where $U_{\mathrm{cr}} \simeq 1.645$ is fixed by the confidence level $1 - \varepsilon = 0.95$. Clearly, by increasing the number of GRBs, we can reach sensitivities for h^2_{RMS} below the standard deviation of the detector noise (i.e., SNR < 1).

3.2. The AURIGA data

We have calculated the U values for the AURIGA data, using a window $W = 3$ s and $N_{\mathsf{off}} = 47\,000$; the results are reported in figure 3. With respect to each GRB trigger, the tested mean delays range from -300 to +300 s with a step of 3 s. It is clear that the experimental U lies below the critical value of 1.645 supporting the null hypothesis $\mathcal{H}_0$. The upper limit $h_{\mathsf{RMS}} = 1.37 \times 10^{-18}$ can be set using equation (11), with $\sigma_{\mathsf{off}} = 6.5 \times 10^{-37}$, $\tau_w = 1.0$ s and $N_{\mathsf{on}} = 190$. To achieve a minimum statistical coverage of 95% we have corrected the upper limit, as given by equation (9). With the help of Monte Carlo simulations we have obtained $\delta h^2 = 1.3 \times 10^{-36}$ and so the upper limit $h_{\mathsf{RMS}} = 1.8 \times 10^{-18}$ ensures 95% coverage.

We have refined our search taking into account the duration T_{50} of GRB which could be the imprinting of two different production mechanisms [1, 3] and probably of GWB emission. According to some models of the GRB central engine [3], short GRBs should be less energetic (two orders of magnitude) in GW emission than the latter. The duration T_{50} is taken from the BATSE data, and it measures the time interval in which 50% of the total observed counts have been detected. The T_{50} interval (defined in [1]) is not available for all the GRB triggers, therefore about 50 GRBs have not been included in this refined analysis. We have separated the remaining GRBs into *short* and *long* GRB sets defined by $T_{50} < 5$ and $T_{50} \geqslant 5$ s respectively; we found $N^{\mathrm{short}}_{\mathsf{on}} = 65$ and $N^{\mathrm{long}}_{\mathsf{on}} = 85$. The scatter plots and histograms of the U variate

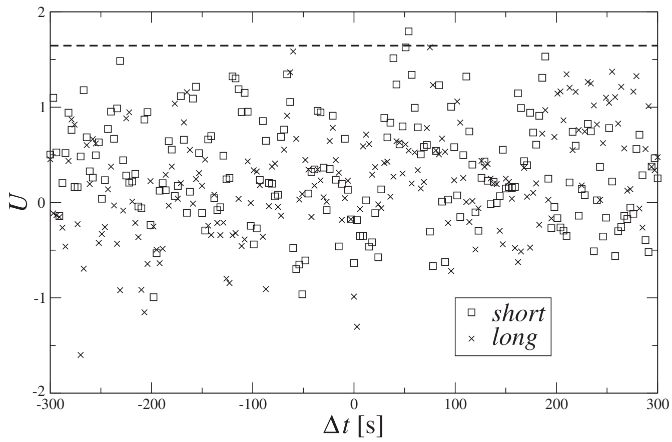

Figure 4. Search applied to the AURIGA data, separating the GRBs depending on their duration: *short* ($T_{50} < 5$ s) and *long*. The dashed line at $U = U_{cr} \simeq 1.645$ represents the critical value for $1 - \varepsilon = 0.95$.

for short and long GRBs are reported in figure 4 for a time span of ±300 s around the GRB triggers. For *short* and *long* GRBs we can estimate the corresponding upper limits, following the already mentioned procedure: $h_{\text{short}} = 2.1 \times 10^{-18}$ and $h_{\text{long}} = 2.0 \times 10^{-18}$.

4. Discussion

The effectiveness of our correlation method becomes troublesome and its sensitivity dramatically decreases when GWB delays have jitters $\sigma_{T_{\text{gw}}}$ larger than the integration window W. This requirement suggests the choice of a large window. Unfortunately, in order to obtain the maximum sensitivity, W cannot be lower than the bound value, $W_b = 3$ s, set by the AURIGA bandwidth. These two criteria make diametrically opposite demands: referring to figure 2, for example, one can see the effect of a factor two in the window amplitude in terms of the critical value of h. In this paper, we have maximized the sensitivity of the time correlation search by choosing the narrowest window W_b and also covered larger mean delays by extending the time correlation search in the ±300 s time span around each GRB. On the other hand, 'naif' approaches to overcome the delay problems would spoil completely the statistical significance of the results. If the GWB–GRB delay is completely random, the only reasonable approach is the cross-correlation of the output of two or more different gw detectors [14–16]. In fact, as the GRB position in the sky is known, the relative phase of the GWB signal in the two detectors can be inferred and cumulative cross-correlation techniques can be used. However, our analysis is much simpler and works effectively if $\sigma_{T_{\text{gw}}} \leqslant W_b$; it seems to be reasonable for many inner engine models as general relativity at event horizon formation is invoked to account for GWB emission. Due to the larger dataset, the better performance of the AURIGA detector in 1999 and the improved search method, the upper limit turns out to be more robust than the previous one [6], covering, in addition, a larger part of possible mean GRB–GWB delays.

5. Conclusions

We have proposed a novel method to find statistical association between GWB and GRB, by means of the Mann–Whitney test. Monte Carlo simulations using the AURIGA data have been performed and compared to the algorithm sensitivity estimations. The effectiveness of the proposed method relies on the assumption that the jitter of the GWB delays is smaller than the integration window. We found no evidence of concurrent emission of GWB and GRB. In addition, we were able to set the upper limit on the averaged gw energy released in ±300 s around the GRB triggers, obtaining $h_{\mathsf{RMS}} = 1.8 \times 10^{-18}$ at 95% confidence level with a statistical coverage greater than the confidence level. This value is an improvement on our previous result [6]. We made use of the classification of *short* and *long* GRBs and the corresponding upper limits have been evaluated as $h_{\text{short}} = 2.1 \times 10^{-18}$ and $h_{\text{long}} = 2.0 \times 10^{-18}$. The level of sensitivity we have obtained could be of astrophysical interest but much work has still to be devoted for operating gw detectors with better sensitivity and with enhancement of noise stationarity. The most appealing feature of GWB searches triggered by a GRB emission is represented by the relation $h^2_{\mathsf{RMS}} \propto h^2_{\min} \big/ \sqrt{N_{\mathsf{on}}}$ (see equation (11)) which implies that correlation methods can reach sensitivities below the noise variance of a gw detector. The almost daily detection of GRBs suggests that, after a year of data taking, we can increase the sensitivity by a factor $\sim\sqrt{400} = 20$, i.e. we can gain a factor ~4.5 in the survey distance of a gw detector. However, further improvements of the upper limit or the claim of a correlation of GWBs and GRBs, can be achieved with a substantial increase of the detector sensitivity and bandwidth. For instance, an increase of two orders of magnitude of the sensitivity of our method could be achieved in the next run of the AURIGA detector [7], where a noise power spectral density better than $S_h^{1/2} \sim 10^{-22}\ (\text{Hz})^{-1/2}$ is expected over a bandwidth of ~80 Hz.

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