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Algorithms for search of correlation between GRBs and gravitational wave bursts

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Abstract. The problem to search for possible correlation between the Gamma Ray Bursts of still unknown origin and data recorded with the Gravitational Wave detectors is studied. A new algorithm for this search based on the Kolmogoroff comparison of distributions is given, which is not affected by the presence of non-gaussian noise.

Key words: gravitational waves – methods: data analysis – gamma rays: bursts

1. Introduction

As well known one of the most important astrophysical phenomena still lacking an explanation, although well known to the scientific community since many years, is the occurrence of powerful GRBs, lasting several seconds, observed near the Earth with spacecraft. Since 1997 (Costa et al. 1997; van Paradijs et al. 1997; Kulkarni et al. 1998) several counterparts in other bandwidths, X-ray, optical and radio afterglow, have been observed. This discovery provides an important tool for understanding the sources of GRBs but most of questions are still open. It is plausible that the phenomena responsible for the emission be due to collapsed objects, perhaps to the coalescence of compact binary systems (Thorne 1992; Piran 1992) or gravitational collapse to a Black Hole (Ruffini 1999). If so, the GRBs should be associated with the emission of Gravitational Waves (GW). According to several authors (Ruffert et al. 1997; Janka et al. 1999) the duration of a GW burst is of the order of a few milliseconds, as predicted by several models (coalescing and merging BH/NS and NS/NS). Therefore the GW burst can be detected by the GW bar detectors, which have their best sensitivity near 1 kHz.

An initial analysis of the time correlation between GRBs and GW detector EXPLORER data has been performed (Astone et al. 1999; Amati et al. 1999). In these cases the method was to select bursts with a fixed threshold on the background of the GW detector. No correlation resulted for events with amplitude h $\geq 2.5 \cdot 10^{-18}$ (about 100 mK in energy).

The main problem in searching for a time correlation between GW bursts and GRB is the uncertainty in the time scale of the possible correlation. The scenario for the proposed GRB progenitors is vast(Rees 1994), allowing for various mechanisms of association. A good way to classify the GRB is by means of their time duration. With a significative statistics there are at least three classes of GRBs (Mukherjee et al. 1998). Furthermore, even within one class, the bursts exhibit a wide range of complex temporal behaviours.

Problems related to the experimental search for time correlation between GW bursts and GRBs have been recently studied by Finn et al. (1999). They suggest that, because of the limited sensitivity of the present and near future GW detectors, one should use methods of data analysis based on cumulative algorithms, and *without specifying a priori models for the signal wave-form, source or source population.*

Because of the ample variety of possible models we have considered in general the case of a time shifted coincidence between the two phenomena, searching essentially an effect, in terms of time signature, in the background of the signals obtained with GW detectors.

The first step, in this paper, consists in applying the simple algorithm of averaging the experimental data at times in correspondence to various (fictitious) GRBs. We shall see that the noise of the real data is such to jeopardize this simple algorithm, thus we shall consider a new algorithm where the real experimental noise is properly taken into account.

2. The experimental data

The GW raw data recorded with a resonant antenna are usually filtered with an algorithm that is matched to delta-like signals, for obtaining the SNR of short GW bursts as large as possible. In the following we shall consider a Wiener-Kolmogoroff filter, like that used by the Rome group (Astone et al. 1994). At the output of the filter there is a sequence of samples (sampling times of 0.29 s) expressed in kelvin units. At present the bandwidth of the detectors around their resonance frequency is of the order of 1 Hz, which means that the correlation time of the filtered data is of the order of one second. The average value of these samples, in absence of GW signals, is called the effective temperature $T_{\rm eff}$ of the apparatus.

It can be shown that the probability for a sample to have energy equal or greater than a given value E, in presence of well

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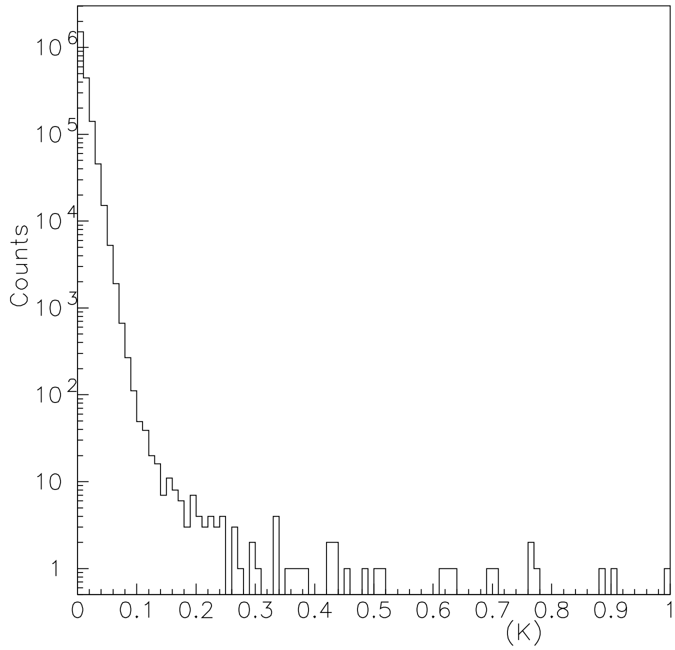

Fig. 1. Differential energy distribution of all samples in 91 periods of two hours each, versus the energy.

behaved noise originated from Brownian and electronic noises both of gaussian nature, is

$$p(\geq E) = \exp(-\frac{E}{T_{\rm eff}}) \quad (1)$$

In addition to the well behaved and modeled noise (electronic and thermal noise), other sources of noise are active, sometimes of unknown origin. Therefore the statistical behavior of the data is not predictable.

For testing our algorithm we use the Explorer data (Astone et al. 1993). For each day, in the time period from June 1991 to December 1997, we take a random time t_γ (simulating the arrival of a GRB) and consider 24001 Explorer samples, corresponding to a period of 1.9388 hours (since the sampling time for Explorer is 0.29081 s) centered at each t_γ time. These two-hour periods include the possibility of a time shift between the t_γ times and the GW arrival time.

We accept only the Explorer data that have, over the two hour-periods, average noise temperature $T_{\rm eff}$ smaller than 10 mK (corresponding to $h \approx 8 \cdot 10^{-19}$). Applying this data selection we get, for Explorer, GW data for 91 periods of about two hours each, centered at the 91 t_γ times. The overall energy distribution of the 91 x 24001 samples is shown in Fig. 1.

This figure shows that, for the Explorer data, in spite of our selection criterion for the choice of the two-hour periods, a large tail appears, giving rise to two slopes. The smallest one of about 10 mK, corresponds to our selection criterion. The largest one is about twenty times greater. This last slope is due to the effect of additional non- stationary noise, which we have to consider carefully when comparing different data distributions. This tail is present, to our knowledge, in all the data so far available from all GW detectors.

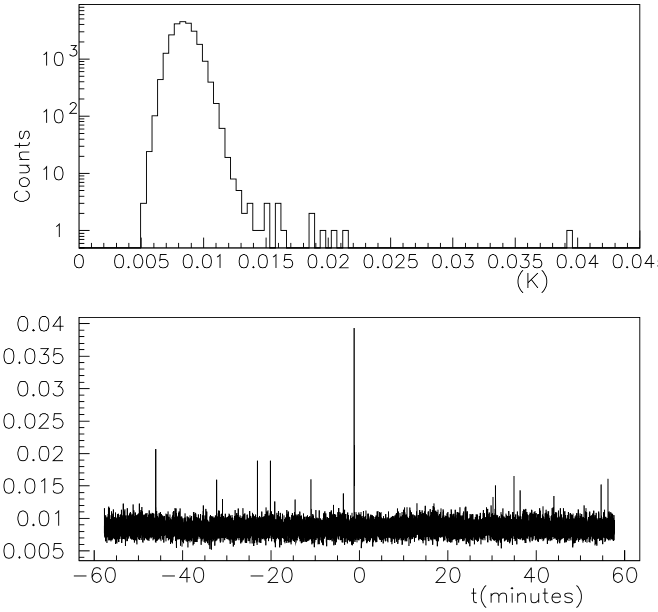

Fig. 2. Explorer data. Sample averaged over 91 data stretches. No signals have been added to the data.

An obvious algorithm to use for searching a correlation between the GRBs and possible GW signals, with the hypothesis that GW are associated to the GRBs with similar behavior for most of the bursts, is to take averages (Modestino & Pizzella 1997).

Since the filtered samples have a time correlation of the order of 1 s, in order to have independent data we take ten-sample (2.91 s) averages, $E_k(t)$, for the k^{th} (k=1,...,91) GRB stretch of GW filtered data. Then we take

$$E(t) = \frac{1}{91}\sum_{1}^{91} E_k(t) \quad (2)$$

at the same relative time t with respect to the arrival times t_γ. This procedure would increase the signal to noise ratio, if the noise reduce as the root square of N.

We have applied this average procedure to the Explorer data selected as described above, and we show the result in Fig. 2. We notice several peaks, one of them near the zero time, due to noise that cannot be modelled. We remark that the noise producing the peaks is not gaussian.

Our problem which we discuss in this paper, is to find a method to reduce the effect of the non-modelled noise.

The GW detectors are so sensitive that some of the noise affecting them, except for the Brownian and electronic noise, cannot be fully modeled. Other sources of noise are present which do not follow any known model. One can have non-modeled disturbances in few data stretches, occurring in a way that might be different for the various stretches of GW data which are associated to the various GRBs. As a consequence, the reduction of the noise with $\sqrt{N}$ fails and unexpected noisy signals jeopardize the average algorithm.

Only for a much larger number of GRBs (many thousands, as predicted by the central limit theorem) the algorithm of the

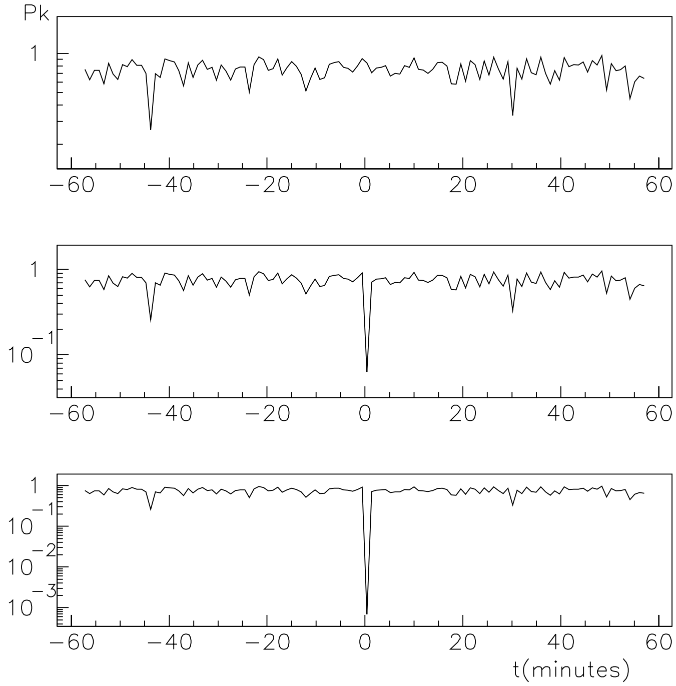

Fig. 3. The Kolmogoroff parameter P versus the time lag. The upper figure shows the result for the 91 data stretches. The middle one shows the result for the same data having added a 10 mK signal at zero time delay. In the lower figure, the same parameter is shown for a 16 mK added signal.

average may give good results. In the following we shall describe an algorithm that circumvents the problem of the non-modeled noise. We shall show that this algorithm appears to give good results when applied to data taken with GW resonant detectors.

3. A new algorithm

Initial developments of the algorithm which we discuss here have been presented at conferences (Modestino et al. 1997, 1998). The algorithm basically operates in two steps: a) we select the 91 GW data stretches recorded at the various t_γ; b) with these data we perform two types of averages. One average, which we call *in- phase* average, is done at the same relative times over the 91 stretches of GW data. The other average, the *off-phase* average, is done in the same way but having randomly changed the relative times of the GW data corresponding to the 91 t_γ times. By taking the in-phase averages we increase the signal-to-noise ratio under the hypothesis that GW signals arrive at the same relative times. The off-phase averages determine the background to which we compare the in-phase averages. By means of the Kolmogoroff test (Eadie et al. 1971), we compare the distribution of the in-phase averages with the distribution of the off-phase averages and obtain the probability P that the two distributions are compatible.

It is clear that if the various stretches have no correlation these two distributions should be compatible one with the other, since, by the circular time shifting within each period, we have been careful to use the same experimental data for both distributions.

In other words, if a strong noise peak is present, it appears in both the in-phase and off-phase distributions and we do not get a minimum in the P distribution. Only if a strong peak occurs at the same time in a sufficiently large number of stretches, only in this case we have a peak in the P distribution.

Note that P does not have the meaning of probability, although obtained with the Kolmogoroff method, because the experimental data do not have normal distribution, as shown in Fig. 1.[1]

The comparison of the distributions is done using 200 samples of data, which cover 58.162 seconds centered at $t_\gamma = 0$. In order to estimate the background of the P quantity we repeat this procedure using different 200 samples centered at different values of t_γ. In a period of about two hours we obtain 120 Kolmogoroff probability values P at 120 different values of t_γ.

This algorithm, applied to the Explorer data, gives the result shown in Fig. 3.

We notice that the small applied signal, respectively with SNR $\simeq 1$ and SNR $\simeq 2$, are well visible above noise whereas in the average distributions these signals would have been confused among those due to the noise. We notice that the Kolmogoroff parameter values do not average at fifty per cent, as one could presume if they had the meaning of probability, but they average at a larger value. This is because the two compared distributions are made essentially by the same experimental data, so they are partially compatible.

However they can be more or less compatible depending on the effect of the in-phase procedure. This is what we measure with the Kolmogoroff $probability$ which has to be taken, as stated above, as an useful parameter rather than the true value of the probability.

In Fig. 4 we show the result when we add at near zero delay (with respect to the GRB arrival time) various signals. In this way we test the sensitivity of the algorithm for the case when GW do not arrive at exactly the same time with respect to the gamma burst. The probability to detect a signal depends on the distribution of the noise as shown in Fig. 3 or in Fig. 4. We understand that is an empirical method but it remains difficult to express in a statistical mathematical sense a non-gaussian noise. For comparison we show in Fig. 5 what we obtain when applying the average algorithm. The signal get lost in the noise, unlikely the result shown in the lower plot in Fig. 4. In the case when one knows exactly the time lag between the two phenomena, as in the case of signals in the GW detectors due to cosmic rays (Astone et al. 2000), the average algorithm might be superior, as one is limited to the analysis of very short stretches of data which allow a better $cleaning$ procedure for eliminating non-modelled noise.

[1] We stress the importance to compare distributions made with the same experimental data, although properly reshuffled as we do. If the two distributions that are compared are made with different experimental data, the presence of data which do not follow the normal distribution makes the two distributions very incompatible.

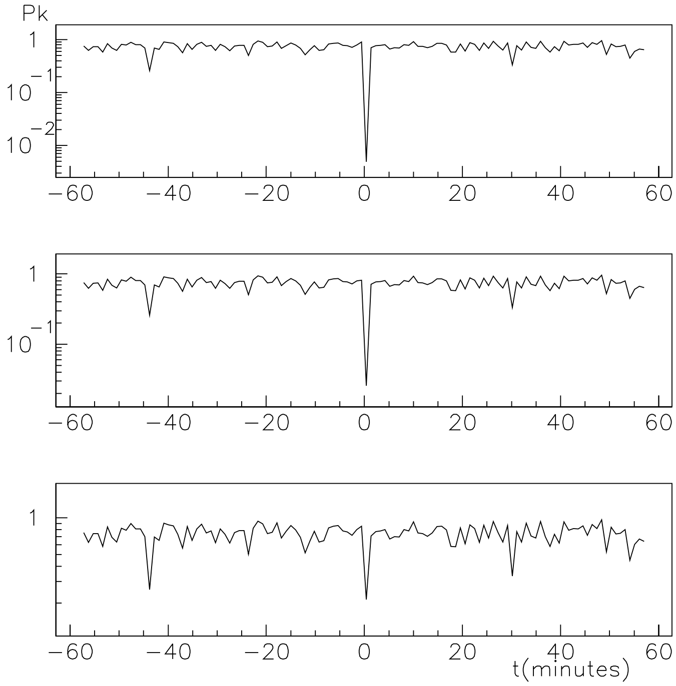

Fig. 4. The Kolmogoroff parameter P versus the time lag. Signals of 16 mK have been added. In the upper figure the 91 added signals have been applied during the same minute centered at zero time but packet at a 20 s time interval. In the middle figure at a 15 s time interval. In the lower figure at a 10 s time intervals.

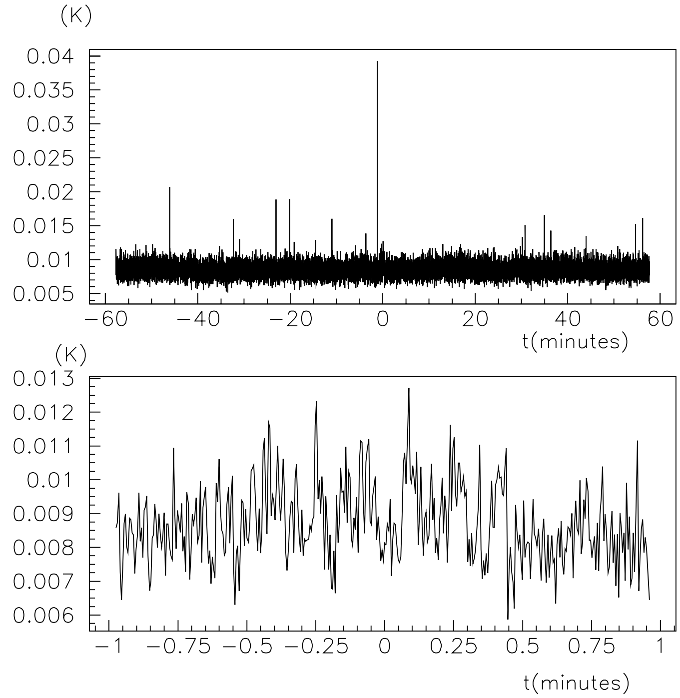

Fig. 5. Average values versus time. 91 signals of 16 mK have been added on six different delays at 10 s time interval in the minute centered at zero time. The lower figure is a zoom of the upper one.

4. Discussion and conclusion

We have seen that using a relatively small number of GRBs (we have used 91 events) the presence of non gaussian noise jeopardizes the use of the average algorithm. Instead, the proposed algorithm presents the advantage to be independent on the quality of the data. Even if extra noise is present, the noise is considered both in the in-phase and off-phase distributions, and only the time alignment makes the difference. Thus one can evaluate possible correlation between GRBs and G.W. signal without the need to accumulate a very high number of events, as in the present experimental situation

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