

# Coincidence analysis in gravitational wave experiments

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Received 9 October 2001, in final form 24 October 2001

Published 11 March 2002

Online at [stacks.iop.org/CQG/19/1443](http://stacks.iop.org/CQG/19/1443)

## Abstract

In the search for gravitational wave burst signals, the coincidence of two or more detectors is necessary. We outline here some of the problems that arise when performing a coincidence analysis, given the fact that the detectors have, in general, different sensitivities.

PACS number: 0480N

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Resonant detectors of gravitational waves [1] have been operating for many years.

The search for short bursts of gravitational radiation is based on the coincidence of detectors that have been operating simultaneously and have produced ‘event’ lists, obtained by optimal filtering procedures applied to the raw data. For each detector, the sensitivity to bursts  $h$ , defined as the dimensionless amplitude of a signal with  $SNR = 1$ , depends on the noise spectral amplitude,  $\tilde{h}$ , expressed in  $\text{Hz}^{-1/2}$  and on the bandwidth  $B^4$ . Up to now, four papers with results of coincidence analyses done using cryogenic resonant detectors have been published [2–5]. The analysis has been done using:

- 180 days of Explorer and Allegro data, taken from June until December 1991. No significant coincident excitations have been found and an upper limit on the rate of g.w. bursts has been put (less than 0.03 events/day at the level  $h > 2 \times 10^{-17}$ );
- 57 days of Explorer and Nautilus data, taken from February until November 1996, and 56 days of Explorer and Niobe data, taken from June until October 1995. No significant excess has been found, but various problems intrinsic to the coincidence analysis have been studied (coincidence window, data selection, energy ratio (see also [6]) or direction filters);

<sup>4</sup> In the approximation of constant  $\tilde{h}$ , for  $SNR = 1$  and for a 1 ms burst, we get  $h = \frac{\tilde{h}}{0.001} \sqrt{\frac{2}{\pi B}}$ .

- 260 days of common observation with two or more detectors of the IGEC [7] collaboration, from January 1997 until December 1998. No excess of coincidences has been found. The previous upper limit has been improved by a factor of three (less than 0.01 events/day at the level  $h > 2 \times 10^{-17}$ );
- 94.5 days of Explorer and Nautilus data, taken from June until December 1998. The aim of this analysis, done on a subset of data exchanged within the IGEC collaboration, has been to study new algorithms for the coincidence analysis, based on the characteristics of the detectors.

A new analysis within the IGEC collaboration is now running on data taken from January 1997 until December 2000. Preliminary results are given in [8]. We note that, over the total observation time of 1460 days, the time coverage, defined as the time over which at least one of the five detectors was working, is 1322 days<sup>5</sup>.

## 2. Basics figures of the coincidence analysis

The general strategy that, up to now, has been followed to perform a coincidence analysis can be schematized in what follows:

- each group filters its own data, using Wiener filters or filters matched to delta-like **signals**, and produces **events** above given thresholds<sup>6</sup>. The threshold depends on the detector sensitivity and is thus a function of the time;
- vetoes on the noise and/or on the events are applied separately by each group, before the data exchange;
- the coincidence analysis procedure is based on the ‘time shift procedure’ (see, for example, [9] and references therein).

Using the data of the two detectors Explorer and Nautilus, and simulations done adding delta-like signals to them, we have recently studied [5, 10] some of the practical problems and tested new algorithms. The problems that we have analysed are:

- the sensitivity of the detectors varies with time;
- the sensitivities of the various detectors are, in general, different;
- a consequence of the previous item is that the same signal generates, in the different detectors, events that give a different estimation and have a different uncertainty on the energy and on the time of arrival.

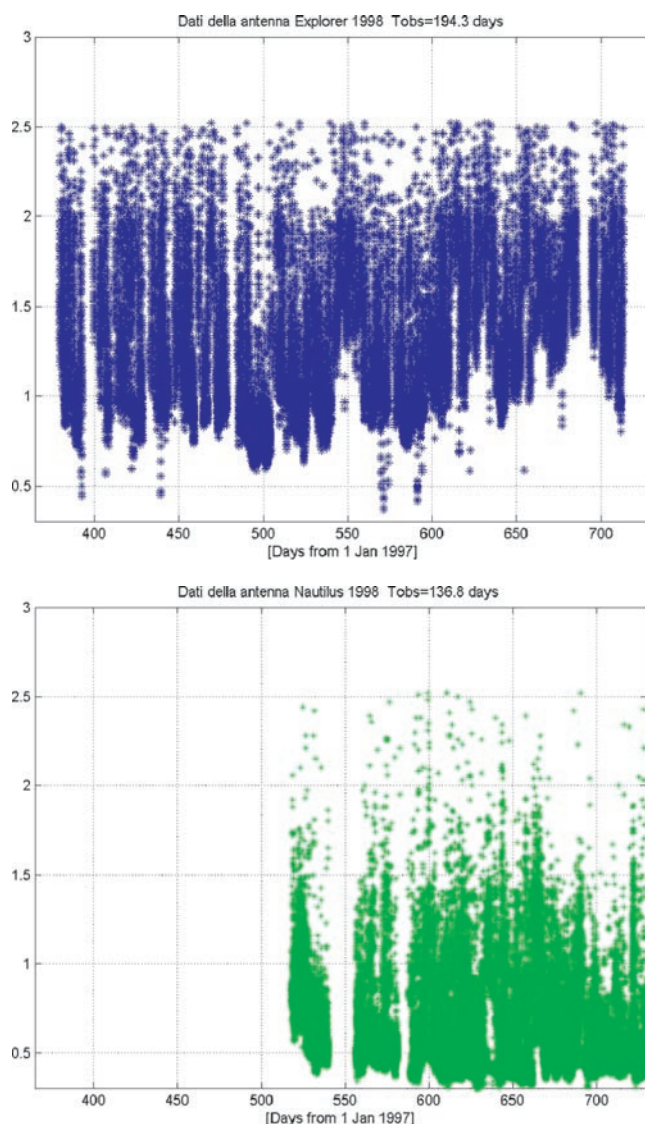
We will limit the discussion here to the problem of the energy of the events, and we will not discuss the time uncertainty and the consequent choice of the coincidence window.

Figure 1 shows the Explorer and Nautilus sensitivity to bursts ( $SNR = 1$ ) during the run of the year 1998. It is not difficult to be convinced that, for example, signals with amplitude  $h = 3 \times 10^{-18}$  can be seen, on average, with good SNRs using Nautilus, and with much poorer SNRs using Explorer. However, in any case, it is still worth doing the coincidence analysis<sup>7</sup>.

<sup>5</sup> That means, in the case of an astronomical trigger, a time coverage of 90%.

<sup>6</sup> We use **signals** to indicate the value of  $h$  that has hit the bar and **events** to indicate the quantity measured by the apparatus, after the proper filtering procedures.

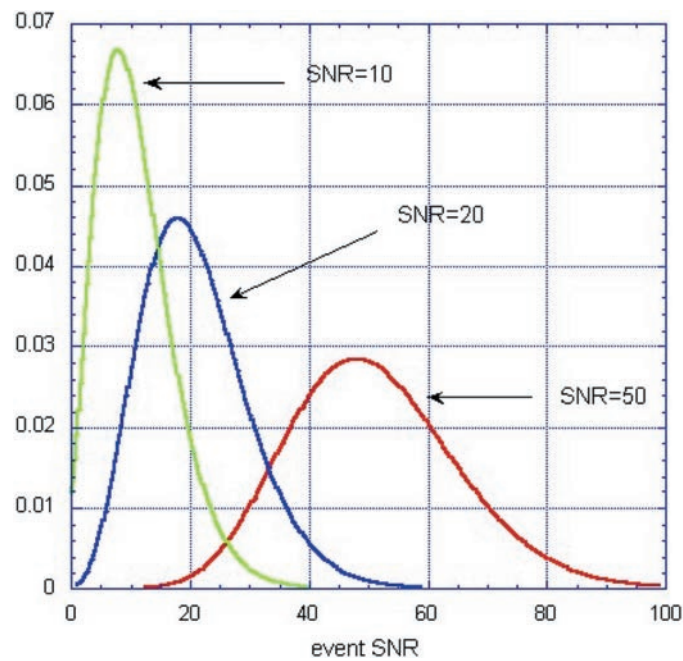
<sup>7</sup> That cannot be done by simply thresholding the data and ignoring all the events obtained when the detector threshold was above the analysis threshold. This would correspond to the rough assumption that the efficiency of detection is one, when the detector threshold is below the analysis threshold, and zero, when the detector threshold is above the analysis threshold.



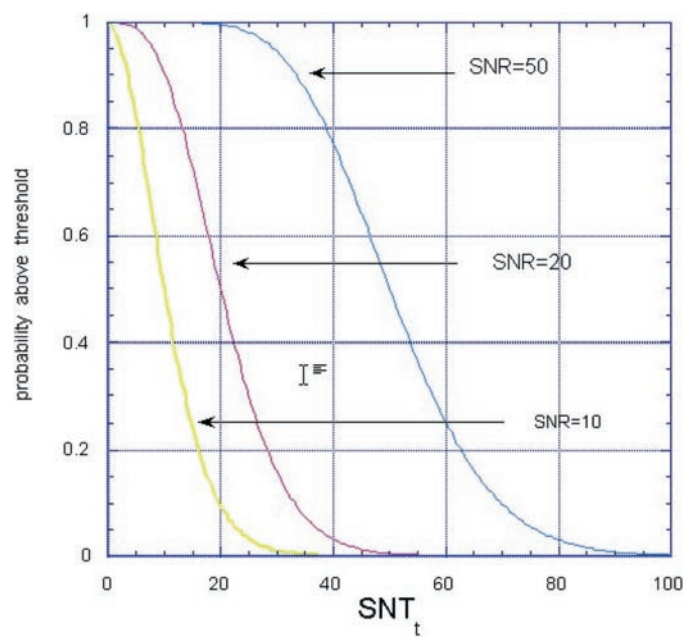
**Figure 1.** Explorer and Nautilus sensitivities to delta-like bursts, for  $SNR = 1$ , during the year 1998. The  $x$ -axis gives days from 1 January 1997. The  $y$ -axis is  $h \times 10^{18}$  (ranging from  $3 \times 10^{-19}$  up to  $3 \times 10^{-18}$ ).

Figures 2 and 3 show, for given **signals** impinging on the detector with energy  $SNR_s = (10, 20, 50)$ , the probabilities, differential and integral, of getting various  $SNR_e$  for the **events**. The mathematics of the problem has been described in various papers (see, for example, [10]). For example, if the threshold has been put, in both detectors, at  $SNR_t = 20$  and if the signal is such to have  $SNR_s = 50$ , using Nautilus, and  $SNR_s = 20$ , using Explorer, then the *probability of detection* is 1 for Nautilus and 50% for Explorer<sup>8</sup>.

<sup>8</sup> If the signal is lower, for example  $SNR_s = 15$  (that is, lower than the chosen detector threshold), there is still a probability of 30% of detecting it.



**Figure 2.** Differential probability of detecting signals with  $SNR_s = (10, 20, 50)$ . The  $x$ -axis gives the SNR of the event,  $SNR_e$ . This figure gives also the energy spread measured by the events, for the given signals.



**Figure 3.** Probability of detection (integral) of signals with  $SNR_s = (10, 20, 50)$ , as a function of the SNR of the threshold,  $SNR_t$ . If we use the threshold  $SNR_t = 20$ , as usual, the graph shows that, for example, the probability of detecting a signal that has  $SNR_s = 20$  is 50%.

### 3. The algorithm for coincidences

Given the previous considerations, we have proposed the use of an algorithm in the coincidence analysis based on the selection of the events on the basis of their compatibility with given signals<sup>9</sup>.

- for given  $SNR_s$  of the signal, there is a chance of obtaining certain  $SNR_e$  of the event, as shown in figures 2 and 3;
- hence we have to assume various signal values, for which the analysis will be done. In the 1998 Explorer–Nautilus analysis we have used the range  $h = (1 \times 10^{-18} - 1 \times 10^{-17})$ , incremented in steps of  $h = 1 \times 10^{-18}$ ;
- for each  $h$  value of the signal, we evaluate  $SNR_s$ , that is a function of  $h$  and of the local noise of the detector;
- we accept the event, and thus the coincidence, if  $SNR_e$  falls into  $SNR_s \pm 1\sigma$ , where  $\sigma$  is evaluated from the probability curves given in figure 2;
- the previous step is repeated for both the coincidences real or shifted and for all the chosen signal values  $h$ .

This algorithm can be improved, by using the experimental probability curves<sup>10</sup>. The application of this method to the coincidences of Explorer and Nautilus [5] has reduced the number of accidentals by a factor of four (the background has reduced from  $n_b = 231.7$  to  $n_b = 50.5$ ).

### 4. On the procedure to put upper limits

We remark here that the same considerations apply to the procedure to put upper limits for burst signals. The algorithm that has been used in the past [12] does not fit with the following items:

- the energy of the measured event is not the energy of the signal;
- the efficiency of detection, for various thresholds and for the chosen source distribution over the sky, has to be taken into account.

Thus, a new algorithm to evaluate upper limits for a given source distribution over the sky has been proposed [13].

### 5. Conclusions

We have reviewed here some basic figures of the coincidence analysis. In particular, we have analysed two important problems: the sensitivity of each detector may vary with time, and the sensitivities of the various detectors may be different. An algorithm aimed at solving these problems, based on the different responses of the various detectors to the same signals, has been presented.

<sup>9</sup> The algorithm is very similar to the **h-veto**, used by B F Schutz and collaborators in the analysis of 100 h of data of two prototype interferometers, in March 1989 [11].

<sup>10</sup> This can be done using calibration delta-like signals added to the noise of the detectors, with various  $SNR_s$ , at given times.

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