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SEARCHING FOR TRIPLE COINCIDENCES AMONG THE RESONANT GRAVITATIONAL WAVE DETECTORS AURIGA, EXPLORER AND NAUTILUS IN THE YEAR 2005: A STUDY ON THE COINCIDENCE WINDOW

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Abstract

We report here the results of a study on the search for triple coincidences among the resonant gravitational wave detectors AURIGA, EXPLORER and NAUTILUS in the year 2005.

The main problem we have studied has been how to choose the coincidence window for the best search of triple coincidences. If the window is too small we may loose real coincidences, if the window is too large, we do get all real coincidences, but they are imbedded in a large background of accidental coincidences. We find that the best choice is a window not greater than two or three standard deviations of the time uncertainty of each event.

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Table 1: Exchanged data . Overview of the validated observation periods for the 180 days considered in this analysis. Off-diagonal terms show the two-fold coincidence times.

	AURIGA	EXPLORER	NAUTILUS
AURIGA	172.9 d		
EXPLORER	151.8 d	158.0 d	
NAUTILUS	150.2 d	135.3 d	155.0 d

1 Introduction

A search for triple coincidences among resonant gravitational wave (GW) detectors was done a few years ago with the ALLEGRO, EXPLORER and STANFORD detectors [1], obtaining a null result. Recently this search has been done again within the IGEC collaboration [2] using all the available GW resonant detectors, again giving a null result and setting an upper limit of the order of 2 events per year with the adimensional burst amplitude h greater than 10^{-17}. In the last years the sensitivity of the resonant detectors has been improved, and a new search for multiple coincidences with the detectors AURIGA, EXPLORER and NAUTILUS is under way.

In this note we wish to discuss the problem of the coincidence window. This is a very important issue, because if the window is too small we may loose real coincidences, if the window is too large, we do get all real coincidences, but they are imbedded in a large background of accidental coincidences, that makes more difficult to spot them.

2 Experimental data

In the fig.1 we show the amplitude distribution of the exchanged candidate among the three detectors within the IGEC Collaboration [3].

In the Table 1 the overlapping periods of observation of the single detectors and for two-fold coincidences, while the total period of three-fols coincidences was 130.7 days.

3 The coincidence window

In the search for coincidences one should always compare the number n_{ct} of the true coincidences with the average number $\bar{n}$ of accidental coincidences and its fluctuations. This puts an upper limit to the best choice of the coincidence window w, because for two-fold coincidences $\bar{n}$ is strictly proportional to w (for three-fold coincidences $\bar{n}$ is proportional to the square of w), and we want to maintain the number of accidental coincidences as small as possible. On the other hand we should have a window large enough to allow a

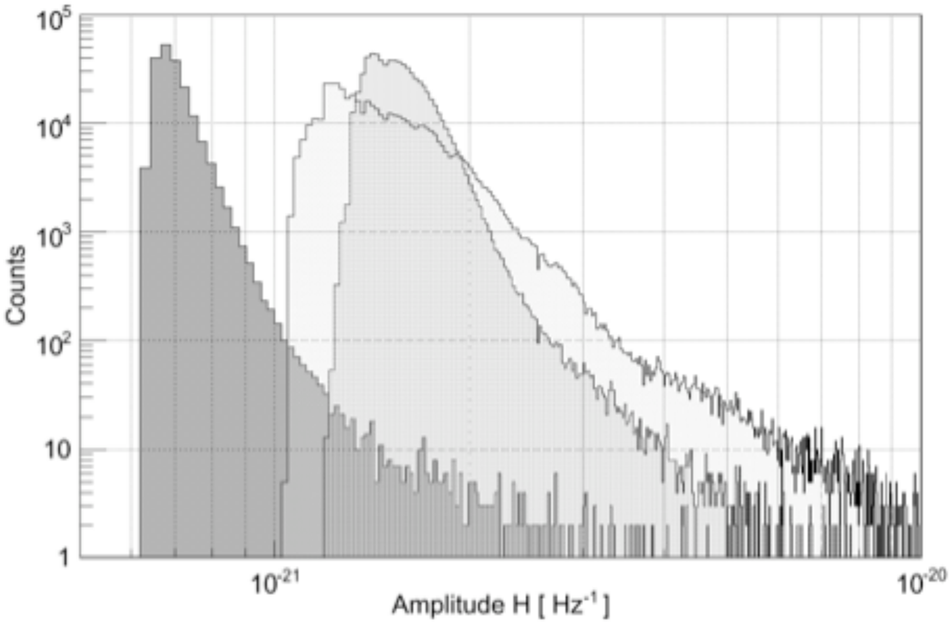

Figure 1: Amplitude distribution of the exchanged candidate events above the minimal thresholds: AURIGA (darker gray) $SNR \geq 4.5$, EXPLORER (lighter gray) $SNR \geq 4.0$ and NAUTILUS (gray) $SNR \geq 4.0$. The amplitude is given in terms of the Fourier component H of the h(t) waveform of a millisecond gw pulse.

good detection efficiency for the true coincidences.

We start by considering the coincidence window between two detectors. In a previous experiment [4] we have used a coincidence window $w = \pm 30\ ms$ on the basis of mesurements [5–8] with cosmic ray showers impinging on EXPLORER and NAUTILUS. We found a time uncertainty of the events due to the cosmic rays with standard deviation of a few ms, typically $4\ ms$ for large signals, tending to increase for small signals, with offsets of the order of 2-3 ms. Thus our choice of $w = 30\ ms$ for the coincidence window was somewhat prodigal, made just for assuring that all, or almost all, the true events were observed.

Since then, we have calibrated[1] [9] the EXPLORER and NAUTILUS apparatuses by software injection of calibration pulses. The result is given in fig.2 for events having signal-to-noise ratio in the range $SNR = 4.0 - 4.25$.

We notice that nearly all true coincidences are detected within $w \sim 30-40\ ms$. The problem is to find the window that is more convenient to use for maximizing the number of true coincidences with respect to the accidental ones.

We have reasoned as follows. The number of accidental coincidences fluctuates around its average value $\bar{n}$ with the Poissonian law and standard deviation $\sigma_b = \sqrt{\bar{n}}$. Thus for a good detection, the number of real coincidences should be greater than a few times σ_b. In other words, we should consider the quantity

$$SNR_c = \frac{n_{ct}}{\sqrt{\bar{n}}} \tag{1}$$

and try to maximize it.

The result of this analysis is shown in fig.3. In this case the optimum window appears to be $w_{opt} \sim 10\ ms$, the window where SNR_c is largest. From fig.2 we note that with $w = \pm 10\ ms$ the efficiency of detection is only of the order of 60%. For $SNR \geq 4.25$ the efficiency is larger.

The above considerations apply well for reasonably large numbers of $\bar{n}$ and n_{ct}. The problem arises in the real case when both $\bar{n}$ and n_{ct} are small, because the Poissonian probabilities depend strongly on the given values of $\bar{n}$ and n_{ct} and the standard deviation method is highly inaccurate. This forces us to an exercise by making some guess about the values of both $\bar{n}$ and n_{ct}.

We have calculated the Poisson probability to have by chance a number of coincidences $n_c = n_{ct} + \bar{n}$ while expecting on average $\bar{n}$, with the values $\bar{n} = 0.1, 0.2, ...1 \frac{1}{100\ ms}$ and $n_{ct} = 3, 4, 5$. The result is shown in fig.4. The average of the values w_{opt} shown in

[1] In ref.[9] we give details of the calibrations, with results both on the detection efficiency and on the time uncertainty.

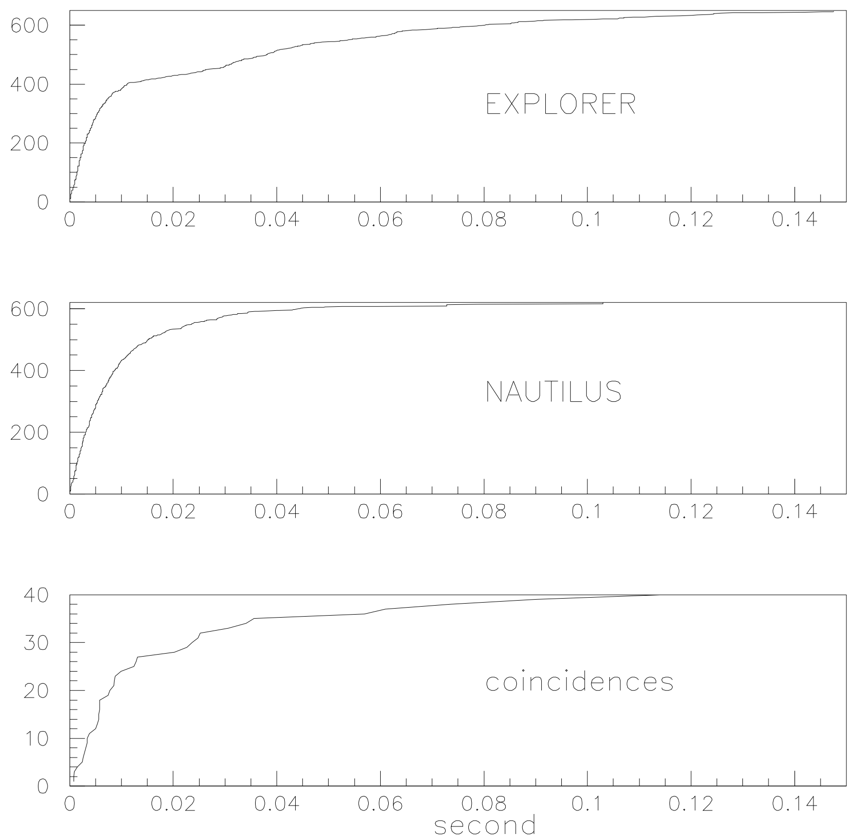

Figure 2: Calibration pulses. In the above two graphs we show the integrated number of pulses versus the time difference between the application time and the time of their detection: 647 pulses applied to EXPLORER (68% at 24 ms) and 620 pulses applied to NAUTILUS (68% at 9.6 ms). In the lowest graph we show the measured integrated number of 40 coincidence events (68% at 13 ms) versus their time difference.

the figure turns out to be of the order of $20\ ms$.

We realize that the choice $w = 20\ ms$ for the coincidence window is rather arbitrary. Our purpose was just to show that a window somewhat larger than 10 ms, but not to much larger, appears to be among the best. For the case of applied pulses with $SNR > 4.25$ a smaller coincidences window is preferable.

4 Detection efficiency

Another problem to consider for small signals is the efficiency of detection, as discussed in refs.[10–12]. The definition of *event*, in order to proceed with the search of coincidences, requires the adoption of a threshold which, in terms of signal-to-noise ratio, we indicate

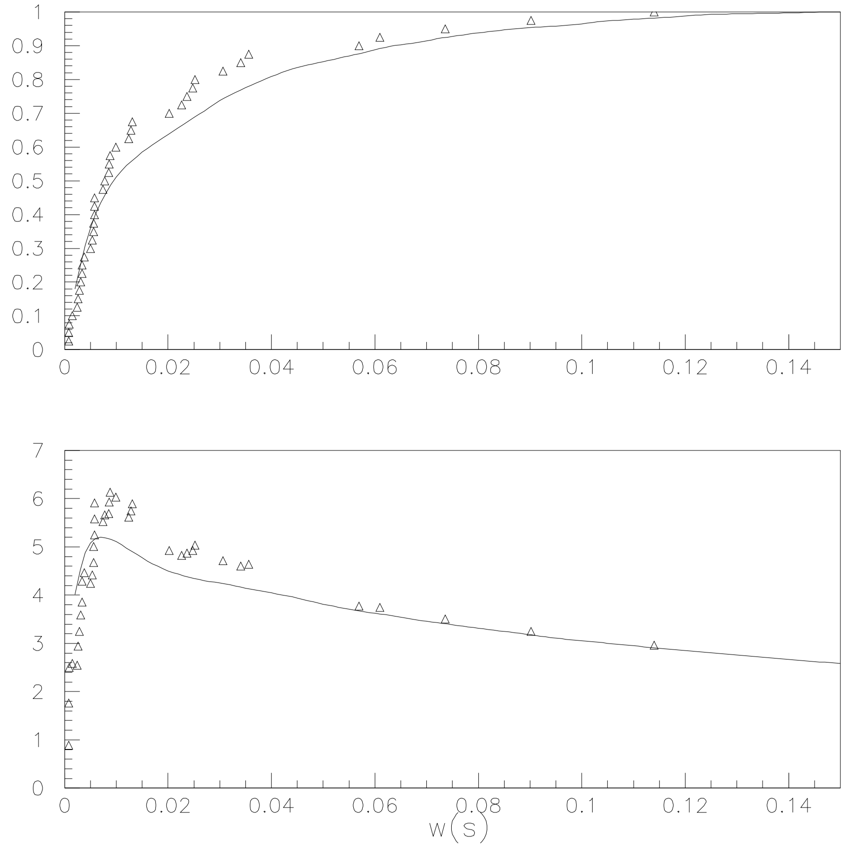

Figure 3: EXPLORER-NAUTILUS coincidences with applied pulses. In the upper graph the triangles indicate the number of observed coincidences with time difference less or equal to w as already shown in fig.2. The continuos line is calculated from the data shown in the upper two graphs of fig.2. In the lower graph of this figure we show the same data divided by $\sqrt{w}$.

with snr_t. Given the effective temperature T_{eff} for the noise of the filtered data, an *event* of amplitude s occurs if $snr = \frac{|s|}{\sqrt{T_{eff}}} \geq snr_t$. It can be shown [13,14] that, in presence of Gaussian noise, if the detector is excited with amplitude $snr = snt_t$, the chance to detect such excitation is of the order of 50%. For the purpose of this note we limit ourselves to the calculated efficiency, which roughly expresses the results of the calibrations given in ref.[9]. The calculated efficiency for the threshold $snr_t = 4$ versus the applied signal $\frac{|s|}{\sqrt{T_{eff}}}$ is shown in fig.5, for the cases of one detector and for the coincidences of two equal detectors.

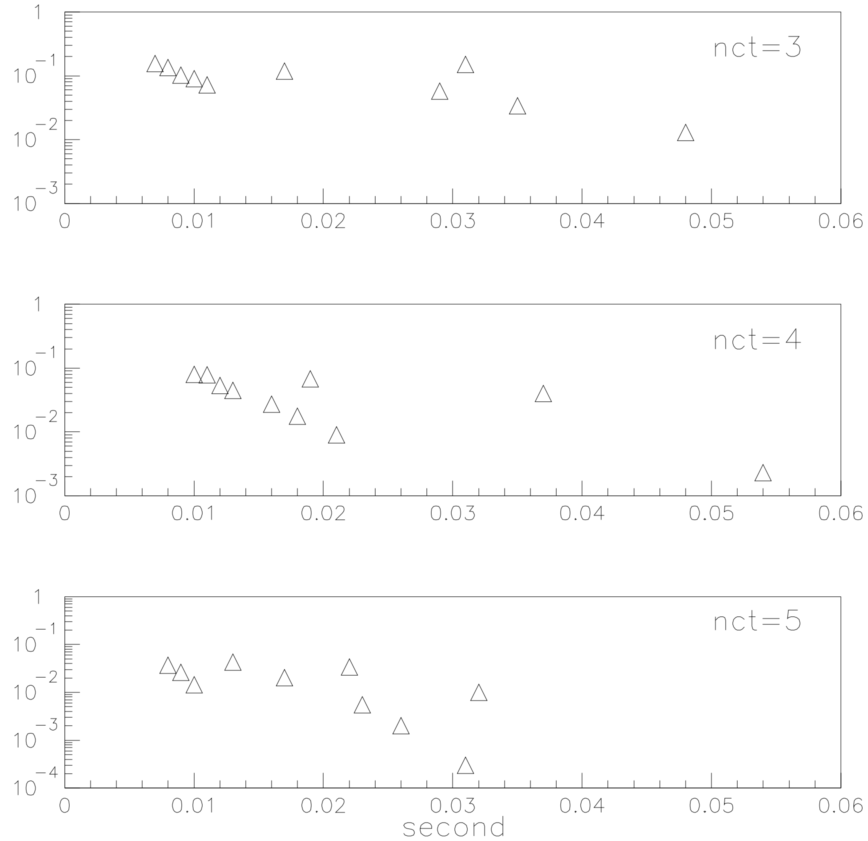

Figure 4: Optimization of the coincidence window for the three cases of true coincidences $n_{ct} = 3, 4, 5$. On the abscissa we report the window which minimizes the Poisson probability to have $n_c + \bar{n}$ by chance, for the ten choices $\bar{n} = \frac{0.1, 0.2, ...1}{100\ ms}$ from right to left. On the ordinate axis these mimimum probabilities are indicated.

5 Experimental results

Because of the greater sensitivity of AURIGA, which has also a smaller uncertainty in the timing (standard deviations of the order of 1 ms), we chose a coincidence window which optimizes the search for double coincidences between EXPLORER and NAUTILUS. We have seen with fig.4 that a possible optimum choice is $w \sim 20\ ms$.

We have now the problem whether to apply the energy filter as done in the previous papers [13,14]. The problem arises when we compare the signal energies of EXPLORER and NAUTILUS with those of AURIGA, because systematical errors may jeopardize the application of the energy filter.

We have two possibilities: a) no application of the energy filter, b) application of

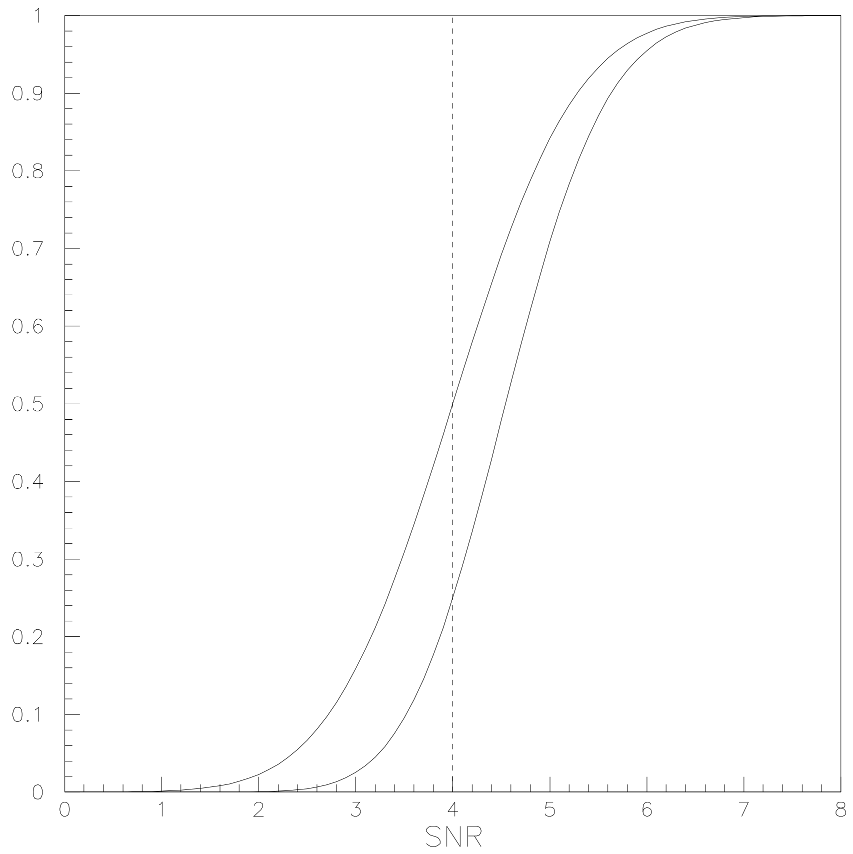

Figure 5: Efficiency of detection versus $\frac{|s|}{\sqrt{T_{eff}}}$. The upper curve refers to the efficiency of one detector, the lower one to the efficiency for detection of double coincidences of two equal detectors, obtained by squaring the upper curve.

the energy filter only to the coincidences of EXPLORER and NAUTILUS. We show the result, in both cases, of a triple coincidence search in the Tables 2 and 3.

In the Table 3 we give, when applying the energy filter, the result with parameter 68% as done in [13,14].

The search for triple coincidences could also have been done in a different way, with much more statistical appeal: just using the coincidence window $w = 30\ ms$ which has been used in a previous search [4], without going trough the above considerations for optimizing the coincidence window. This has the advantage to avoid the statistical danger to make *a posteriori* choices. The result with $w = 30\ ms$ is shown in the Table 4.

Table 2: List of three triple coincidences with the EXPLORER time. d1, d2 and d3 indicate the time differences in ms, respectively between EXPLORER and NAUTILUS, EXPLORER and AURIGA, NAUTILUS and AURIGA.The event energies in mK are also given for the three detectors. In the last column s.h. indicates the sidereal hour.

day	hour	min	sec	d1 ms	d2 ms	d3 ms	expl mK	naut mK	auri mK	s.h.
149	12	37	26.782	-18	0	-18	51	41	7.0	5.1
178	14	35	19.965	0	11	11	35	38	6.7	9.0
194	16	59	53.411	-2	-13	-15	22	29	7.2	12.4

Table 3: Results of the coincidence search with coincidence window $w = 20\ ms$: #expl-naut indicate the number of double coincidences, #auri the number of the AURIGA events, $\bar{n}$ and n_c indicate the average number of accidental coincidences and the number of coincidences. In the last column p indicates the Poissonian probability to have a number of coincidences greater or equal to n_c.

energy filter	#expl-naut	#auri	$\bar{n}$	n_c	p
no filter	1922	187338	0.41	3	$8.7\ 10^{-3}$
68%	1748	187338	0.39	3	$7.3\ 10^{-3}$

Table 4: As in fig.3 with coincidence window $w = 30\ ms$.

energy filter	#expl-naut	#auri	$\bar{n}$	n_c	p
no filter	1922	187338	0.76	3	$4.1\ 10^{-2}$
68%	1748	187338	0.70	3	$3.5\ 10^{-2}$

6 Discussion

The result shown in the Tables 3 and 4 is faced with the problem of the energy compatibility. The AURIGA signals have energies about five times smaller than those of the other two detectors. Only a systematical error of that order (on one or on both sides) would make the result more acceptable.

If we think that the true energy of the event is that given by AURIGA, then the lower curve of fig.5 would show an efficiency near to zero for the double coincidences, which we cannot accept. Of course, it is possible, although with small probability, that the result shown in the Table 3 be due to a background fluctuation.

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References

[1] E.Amaldi *et al.*, *Astronomy and Astrophysics,* **216**, 325 (1989)

[2] Z.A. Allen *et al.*, *Phys.Rev.Lett.,* **85** 5046-5050 (2000)

[3] IGEC-2 Collaboration *Results of the IGEC-2 search for gravitational wave bursts during 2005*, http://arxiv.org/abs/0705.0688 (2007)

[4] P.Astone*et al.*, *Class.Quant.Grav.,* **23**:S169-S178,2006

[5] P.Astone *et al.*,*Phys.Rev.Lett.* ,**84** 14-17 (2000)

[6] P.Astone *et al.* , *Phys.Lett.* ,**B499** 16-22 (2001)

[7] P. Astone *et al.*, *Phys.Lett.* ,**B540** 179-184 (2002)

[8] G.Modestino, G.Pizzella and F.Ronga, *Calibration of the Resonant Gravitational Wave Detectors Explorer and Nautilus in 2003 and 2004 Using Cosmic Rays,* Internal Report Frascati, LNF - 05 / 27(IR) (2005)

[9] G. Giordano - *Iniezioni software*, http://www.lnf.infn.it/esperimenti/rog/

[10] P.Astone, G.V.Pallottino and G.Pizzella, *Gen.Rel & Grav.,* **30,** 105 (1998)

[11] P.Astone, S.D'Antonio and G.Pizzella, *Phys. Rev.* **D**, 62, 042001 (2001)

[12] G.Pizzella, *GWDAW '98*, Pennsylvania University,19-21 November 1998

[13] P.Astone *et al.*, *Class. Quantum Grav. ,***18**, 243-251 (2001)

[14] P.Astone *et al.*, *Class. Quantum Grav. ,***19**, 5449-5463 (2002)