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# Search for coincident excitation of the widely spaced resonant gravitational wave detectors EXPLORER, NAUTILUS and NIOBE

P. Astone<sup>a</sup>, M. Bassan<sup>b</sup>, D.G. Blair<sup>c</sup>, P. Bonifazi<sup>d,a</sup>, P. Carelli<sup>e</sup>, E. Coccia<sup>b</sup>, C. Cosmelli<sup>f</sup>, V. Fafone<sup>g</sup>, L. Febo<sup>f</sup>, S. Frasca<sup>f</sup>, I.S. Heng<sup>c</sup>, E.N. Ivanov<sup>c</sup>, A. Marini<sup>g</sup>, E. Mauceli<sup>g</sup>, S.M. Merkwitz<sup>g</sup>, Y. Minenkov<sup>b</sup>, I. Modena<sup>b</sup>, G. Modestino<sup>g</sup>, A. Moleti<sup>b</sup>, G.V. Pallottino<sup>f</sup>, M.A. Papa<sup>b</sup>, G. Pizzella<sup>b,g,1</sup>, F. Ronga<sup>g</sup>, R. Terenzi<sup>b,d</sup>, M.E. Tobar<sup>c</sup>, P.J. Turner<sup>c</sup>, F.J. van Kann<sup>c</sup>, M. Visco<sup>b,d</sup>, L. Votano<sup>g</sup>

<sup>a</sup> *Istituto Nazionale di Fisica Nucleare (INFN), Rome, Italy*

<sup>b</sup> *Physics Dept, University "Tor Vergata" and INFN, Rome, Italy*

<sup>c</sup> *University of Western Australia, Perth, Australia*

<sup>d</sup> *Istituto di Fisica dello Spazio Interplanetario, CNR, Rome, Italy*

<sup>e</sup> *University of L'Aquila and INFN, L'Aquila, Italy*

<sup>f</sup> *Physics Dept., University "La Sapienza" and INFN, Rome, Italy*

<sup>g</sup> *Laboratorio Nazionale INFN, Frascati, Italy*

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## Abstract

We report the search for coincidences among three resonant mass detectors: EXPLORER at CERN and NAUTILUS in Frascati of the Rome group and NIOBE in Perth of the UWA group. The three detectors have a sensitivity for short bursts of GW in the  $h \approx 10^{-18}$  range, about one thousand times better in energy than Weber's original detectors. The analysis is based on the comparison of candidate event lists recorded by the detectors in the period December 1994 through October 1996. The events have been obtained by applying a pulse detection filter to the raw data and using a predetermined threshold. Due to the different periods of data taking it was not possible to search for triple coincidences. We searched for coincidences between EXPLORER and NAUTILUS during the years 1995 and 1996 for a total time coverage of 1372 hours and between EXPLORER and NIOBE in 1995 for a coverage of 1362 hours. The results have been: a weak indication of a coincidence excess with respect to the accidental ones between EXPLORER and NAUTILUS and no coincidence excess between EXPLORER and NIOBE. © 1998 Elsevier Science B.V.

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## 1. Introduction

<sup>1</sup> Corresponding author: G. Pizzella, Institute for Nuclear Physics, Frascati, Via E. Fermi 40, 00044 Frascati (Rome), Italy; e-mail: pizzella@inf.infn.it.

Almost 30 years ago, Weber reported [1] coincident excitation of a pair of resonant mass gravitational

wave detectors. Numerous subsequent attempts failed to confirm his observations. The painstaking development of much more sensitive detectors has continued ever since.

After the initial results with room temperature resonant detectors the new generation of cryogenic gravitational wave (GW) antennas entered long term data taking operation in 1990 (EXPLORER [2]), in 1991 (ALLEGRO [3]), in 1993 (NIOBE [4]), in 1994 (NAUTILUS [5]) and in 1997 (AURIGA [6]). Several problems were encountered. The most important one was the problem of nonstationary noise causing varying sensitivity performance. The existence of nonstationary noise means that criteria must be developed for extracting candidate events and vetoing data when performance is sufficiently degraded.

Moreover, the periods of data taking were not continuous because of short interruptions for maintenance operations as well as long stops for instrumental improvements.

Resonant GW antennas can detect signals of various types in the kHz frequency range: (i) short bursts of radiation, such as that expected from the asymmetrical collapse of a stellar core or the plunge of a neutron star into a black hole, (ii) periodic GW such as those emitted by non-axisymmetric pulsars and (iii) stochastic GW due to various possible cosmological sources.

In this paper we report a search for coincident excitations due to short GW bursts using three resonant detectors that are located at large distances: EXPLORER at CERN (Geneva, Switzerland), NAUTILUS in Frascati (near Rome, Italy) and NIOBE in Perth (Australia), in the years December 1994, 1995 and 1996. The data was chosen so that they could all be treated with the same algorithm optimized for the search for GW bursts.

There was no “a priori” reason for requiring the data from each detector to be filtered by the same filtering algorithm. However, it is essential to avoid “a posteriori” choices of the algorithm to maintain the statistical validity of the analysis. The most reasonable way to achieve this is to insist that all data is filtered by the algorithm providing the best sensitivity, if possible the same algorithm. We chose the adaptive Wiener algorithm which has been extensively studied [7,8] and provides good performance even in the presence of nonstationary noise.

Table 1

Periods of available data from the three detectors

detector/year	1994	1995	1996
EXPLORER	1–20 Dec	24 Feb–31 Dec	19 Feb–5 Nov
NAUTILUS	1–15 Dec		10 Jan–5 Nov
NIOBE		29 June – 6 Oct	

In Table 1 we give the periods when the data from each detector was available. It is important to note that while NIOBE was operational in 1996 this data was not used in the present search because we wanted to use the data treated by the same Wiener algorithm and the 1996 NIOBE data was not yet available with this chosen algorithm. For the same reason the Allegro data, treated with a different algorithm, was not considered in this analysis. Analysis of this data will be the topic of a future paper.

Preliminary results of coincidence between EXPLORER and NIOBE were discussed at conferences. In this case less powerful, and different, filter algorithms were used for each detector giving results inconsistent with those reported here. Again we prefer here to present data filtered using the same algorithm, which also provides better sensitivity.

From Table 1 we notice that there were no periods when data from the three detectors was available simultaneously, so it was only possible to search for coincidences between EXPLORER and NAUTILUS and between EXPLORER and NIOBE.

Coincidence analysis provides a strong attenuation of the effects of the intrinsic detector noise as well as external local disturbances. Due to the uncertain nature of possible gravitational waves signals, in comparing the data from the three antennas we have privileged on the statistical aspects of the data analysis. The main problem in any coincidence experiment, as in any statistical analysis, are the analyst’s choices which may reduce or even cancel the final meaning of any result. As detailed in the following sections we have been careful to establish the criteria of the search before beginning the statistical analysis.

In our case the choices are: (a) which detectors will be compared, (b) the time periods for the data used in the analysis, (c) the energy threshold used for defining the events, (d) the choice of the time windows for the coincidences. The first two choices have been already

Table 2  
Antenna parameters

Antenna	NIOBE	EXPLORER	NAUTILUS
Mass bar (kg)	1510	2270	2270
Mass transducer (kg)	0.45	0.40	0.32
Material	Nb	Al	Al
length (m)	2.75	2.97	2.97
Mode Frequencies $f_-$ and $f_+$ (Hz)	694.6	904.7	908.3
	713.0	921.3	923.8
Loaded Quality Factor ( $10^6$ )	30	1.01	2.3
Typical Noise Temperature (mK)	5	15	12
Typical Pulse sensitivity $h$	$1 \times 10^{-18}$	$1 \times 10^{-18}$	$9 \times 10^{-19}$
Antenna position and orientation			
Longitude	115.8° E	6.25° E	12.67° E
Latitude	32° S	46.25° N	41.8° N
Azimuth	0°	39.3°	39.3°

From these parameters, the relation between the noise temperature  $T_{\text{eff}}$  and the pulse sensitivity of the antenna, for 1 ms bursts, is calculated to be  $h = 1.5 \times 10^{-17} \sqrt{T_{\text{eff}}}$  for NIOBE and  $h = 8.1 \times 10^{-18} \sqrt{T_{\text{eff}}}$  for EXPLORER and NAUTILUS.

discussed. The (c) and (d) choices will be considered in the following sections.

## 2. Experimental details

The three detectors, EXPLORER, NAUTILUS, and NIOBE, each consists of a massive bar resonating at its first longitudinal mode of vibration (916 Hz for EXPLORER and NAUTILUS, 700 Hz for NIOBE). For the first two detectors the bars are cylinders of Al 5056 with a mass of 2270 kg. EXPLORER is cooled to  $T = 2.6$  K and NAUTILUS to  $T = 0.1$  K. NAUTILUS is the first resonant antenna making use of ultra low-temperature techniques in order to reduce the thermal noise. The NIOBE antenna is a cylinder of niobium cooled to  $T = 4.2$  K. The characteristics of the three detectors are given in Table 2.

For converting the mechanical vibrations into electrical signals we use resonant transducers resonating at the antenna frequency. For EXPLORER and NAUTILUS, a capacitive transducer is used followed by a superconducting transformer and a dc SQUID amplifier. For NIOBE a parametric transducer is used consisting of a 10 GHz microwave re-entrant cavity followed by a cryogenic GaAs FET amplifier.

The bar with the resonant transducer form a coupled oscillator system, which has two resonant modes, whose frequencies we indicate with  $f_-$  and  $f_+$ .

All antennas use similar data acquisition systems. The signal from the transducer is fed into a pair of lock-in amplifiers tuned to the resonant frequency of each antenna mode. The output of the lock-in amplifiers are sampled at 10 Hz (NIOBE) and 3.44 Hz (EXPLORER and NAUTILUS). The raw data for each detector was filtered according to predetermined procedures. For all detectors an off-line adaptive Wiener–Kolmogorov filter was used, using parameters obtained from the spectral response of the antenna. Events with energies larger than seven times the mean noise energy of the previous 600 seconds of data are automatically extracted as candidate event list.

For EXPLORER, the timing information is checked against a set of 1 Hz pulses from a combined source based on the HBG time standard broadcasting station and a rubidium clock and gives the Universal Time with accuracy of 0.1 seconds. The NAUTILUS timing is checked against the data of time standard broadcasting stations. The UWA timing has been verified by a Global Positioning System (GPS). However, for this initial experiment the beginning of each run for UWA is determined manually with maximum error of  $\pm 0.5$

s. In addition the beginning time is truncated to the second. Therefore, all together there is a time error of the order of  $\pm 1$  s (after adding 0.5 s for the truncation) that should be considered with respect to the Universal Time.

The detectors have been calibrated as follows. The NIOBE calibration relies on the intrinsic self-calibration of a parametric transducer referred to the tuning coefficient of the microwave cavity transducer element. This is measured by determining the change in resonant frequency when the cavity gap spacing is altered [9,10]. EXPLORER is calibrated by using a small precalibrated piezoelectric transducer to apply wave packets of known frequency, amplitude and duration as well as by using a near gravitational field induced by a rotor [11]. NAUTILUS is calibrated also by using a small precalibrated piezoelectric transducer.

### 3. The algorithms for short burst detection

The candidate events for coincidence analysis are obtained in two steps: (a) by filtering the data recorded by the detectors to obtain estimates of the energy innovation, i.e. the change in the energy status of the bar; and (b) by applying a suitable energy threshold to the energy innovation. We use optimum filters designed to improve the signal to noise (SNR) ratio for short bursts of gravitational radiation, where short means a duration smaller than the sampling time and the time constants of the apparatus.

The estimate of the energy innovations, for each normal mode of the detector, is obtained as follows. We have four channels:  $x-$ ,  $y-$ ,  $x+$ ,  $y+$ , because each mode ( $-$ ,  $+$ ) is represented by the two quadrature components ( $x$ ,  $y$ ) after the lock-in. These data are processed off-line using the adaptive Wiener filter [7], which accounts for the nonstationary nature of the noise of the apparatus (the adaptive Wiener filter generates a new filter function every two hours, based on the measured output noise spectrum).

The corresponding filtered sequences ( $x_{w-}$ ,  $y_{w-}$ ,  $x_{w+}$ ,  $y_{w+}$ ) after proper normalization based on the calibration of the apparatus, are used to construct the energy innovations  $\rho_-^2$  and  $\rho_+^2$  of each normal mode,

$$\rho_-^2 = x_{w-}^2 + y_{w-}^2,$$

$$\rho_+^2 = x_{w+}^2 + y_{w+}^2. \quad (1)$$

The two independent estimates, at each time instant, are finally combined by taking their minimum, which represents the energy innovation  $\rho^2$  of the detector. This quantity is usually expressed in kelvin. The effective temperature  $T_{\text{eff}}$  for each normal mode is defined as the mean value of  $\rho^2$ : it represents the energy sensitivity of the detector for pulse detection in the sense that it gives the smallest energy innovation that can be measured with  $\text{SNR} = 1$ .

The variable  $\rho^2$ , in the absence of signals and of non-Gaussian disturbances, follows the Boltzmann distribution,

$$N(> \rho^2) = N_0 \exp\left(-\frac{\rho^2}{T_{\text{eff}}}\right), \quad (2)$$

where  $N_0$  is the total number of samples.

Candidate events are obtained by scanning the time sequence of the energy innovations. An event starts when one sample exceeds the local value of the noise by a convenient (see later) factor here chosen to be 7.0 and lasts until one of the samples that follows falls below this threshold with a subsequent dead time of 10 s. Since the noise, in general, is not stationary, the noise  $T_{\text{eff}}$  is calculated and adjourned using a moving average over a time of ten minutes. Each event is therefore characterized by its duration and by the time and the energy  $E_{\text{max}}$  of its maximum. The reason of the choice of the moving average and of the value 7.0 chosen for the threshold is to set a convenient value to the number of candidate events. Considering a correlation time of about one second for the data (see below), we have  $N = 86400 \exp(-7) = 80$  candidate events per day, to be used for coincidence analysis. With this moving threshold the event rate does not increase during the noisier periods. Clearly, however, it is important that  $T_{\text{eff}}$  remains below reasonable limits for the data to be useful, as discussed below.

### 4. The data selection

The gravitational wave antennas are very sensitive instruments, more sensitive than any other instrument which can be used to check their performances. Thus, while seismometer, electromagnetic detectors, power line fluctuation monitors and cosmic ray detec-

tors are sometimes useful for eliminating unwanted noise, many times the noise source is unknown [12]. For this reason the coincidence technique is of the uttermost importance.

The sensitivity of this technique depends on the signal to noise ratio (SNR) of the possible GW signals. One approach is to select periods when the SNR is within an acceptable range and to eliminate those periods when the noise is very large. This procedure is very delicate, and it must be applied “a priori” in order not to invalidate the statistical analysis by considering a number of different alternatives.

We have therefore decided to simply a priori eliminate from the analysis the hours where the detector operation is clearly unacceptable. For EXPLORER and NAUTILUS, those hours with average noise  $T_{\text{eff}}$  above the value 100 mK were eliminated. For NIOBE the noise temperature is smaller. Thus we scaled the above value by a factor  $(8.1/15)^2 = 0.29$  under the assumption that the common excitations are due to GWs (0.29 corresponds to the ratio of the cross sections, which depend on the mass of the bar and on the velocity of sound in the material). For the period under consideration, from December 1994 (when NAUTILUS started to record data) through October 1996 (when this data analysis started) we have 1372 hours when both EXPLORER and NAUTILUS were operating with hourly noise temperature below 100 mK. For the period when EXPLORER and NIOBE overlapped (day 180 to day 280 of year 1995) we have 1362 hours when EXPLORER had hourly noise temperature below 100 mK and NIOBE below 29 mK. The objection can be made that at such high level of noise the operation of the detectors was rather poor, so we considered also more conservative data selection: hours with noise temperature below 50 mK and 25 mK for EXPLORER and NAUTILUS, hours with noise temperature below, respectively, 14.5 mK and 7.1 mK for NIOBE. All these three selections must be presented together in the final result.

As far as eliminating data recorded in correlation with seismic or electromagnetic disturbances as detected by the auxiliary channels, this was done for the antenna EXPLORER, reducing the data by about 10%. For NAUTILUS this was not done, as the auxiliary channels were not operative yet. For NIOBE the level of correlation with the auxiliary channels is sufficiently low that veto are not normally needed.

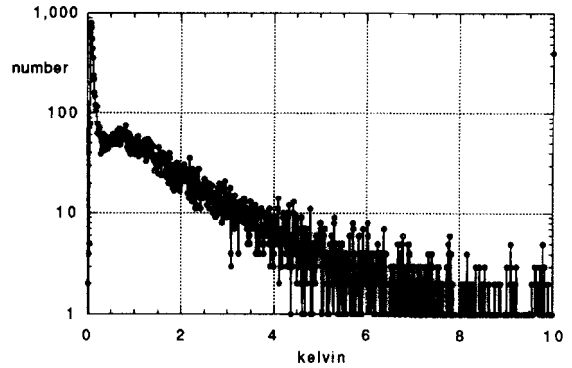


Fig. 1. Distribution of the event energy for EXPLORER during the hours with noise temperature smaller than 100 mK.

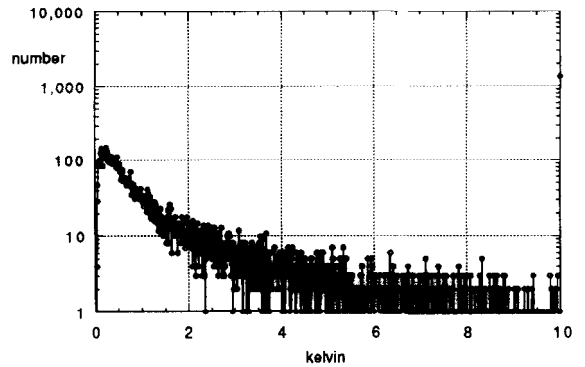


Fig. 2. Distribution of the event energy for NAUTILUS during the hours with noise temperature smaller than 100 mK.

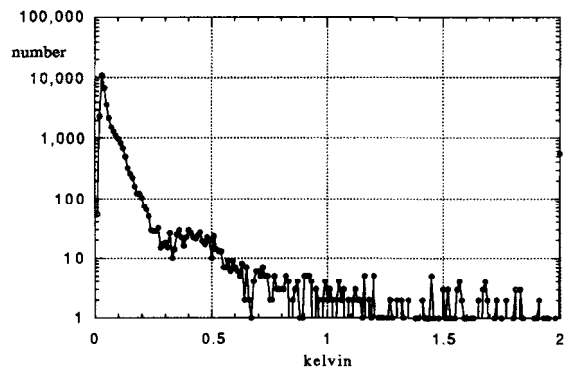


Fig. 3. Distribution of the event energy for NIOBE during the hours with noise temperature smaller than 29 mK.

We show in Figs. 1–3 the distribution of the EXPLORER, NAUTILUS and NIOBE events during the selected periods of time.

Table 3

Simulation for determining an appropriate coincidence window; efficiency of detection as a function of burst energy and coincidence window

$w$ (second)	1 K SNR=70	0.5 K SNR=35	0.2 K SNR=14	0.1 K SNR= 7
$\pm 0.1$	0.65	0.57	0.30	0.076
$\pm 0.3$	0.97	0.94	0.59	0.19
$\pm 0.6$	1.00	0.99	0.71	0.26
$\pm 1.0$	1.00	1.00	0.74	0.27
$\pm 3.0$	1.00	1.00	0.78	0.31

### 5. Choice of the coincidence window

We considered it important to establish the time window for the coincidences before starting the analysis, as to avoid introducing any bias by “a posteriori” selection.

By taking a very small window, one may lose a GW signal because of various reasons: (a) the basic time uncertainty introduced by the filter whose integration time determines the time uncertainty of the events; (b) the effect of the noise, that we know considerably affects the observations even in conditions of relatively high SNR [13]; (c) possible timing errors. If the window is too long, on the other hand, the number of accidentals becomes too large.

To establish the coincidence window for EXPLORER and NAUTILUS, before performing the coincidence analysis of the experimental data, we simulated the raw data of EXPLORER and NAUTILUS using the actual parameters (resonance frequencies, quality factors, temperatures, electronic noise) of the detectors, obtaining a simulated noise temperature of 14 mK very close to the experimental values. To these data, representing the noise, we added 223 signals (detector responses to short bursts), occurring exactly at the same time for the two detectors. This was repeated with different amplitude for the events. The resulting sequences were then processed with our standard procedures, i.e. filtered to obtain the energy innovations and treated with the moving threshold to obtain the events. The last step was to search for coincidences between the two simulated event lists by using time windows of various duration.

The results of this simulation are given in Table 3, where we show the fractional number of coincidences

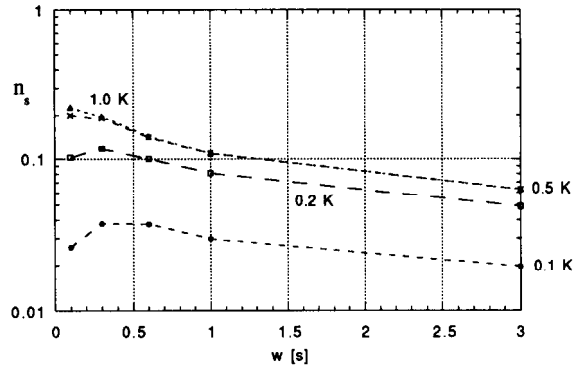


Fig. 4. Number  $n_s$  = efficiency of signal detection, obtained from the efficiency given in Table 3, normalized to the standard deviation, as function of the coincidence window for different signal amplitude.

actually found as a function of both the amplitude of the events (given as burst energy in unit of kelvin) and the coincidence window  $\pm w$ . For these simulations the expected number of accidental coincidences due to the noise processes is smaller than one.

The efficiency of the procedure for determining the best value of the window  $w$ , when applied to the real data, depends, of course, on the absolute numbers of coincidences and accidentals.

The number of the accidentals for the real case can be estimated with the aid of the following formula:

$$\langle n \rangle_{\text{th}} = \frac{N_{\text{expl}} N_{\text{naut}} 2w}{t_m}, \quad (3)$$

where  $t_m$  is the time of measurement and  $N_{\text{expl}}$  and  $N_{\text{naut}}$  are the numbers of events respectively of EXPLORER and NAUTILUS during this time.

A possible coincidence excess has to be compared with the standard deviation  $\sqrt{\langle n \rangle_{\text{th}}}$ , to determine the excess in terms of number of standard deviations. We do not know the coincidence excess, but we can divide the efficiency of detection (as obtained from Table 3) by  $\sqrt{\langle n \rangle_{\text{th}}}$ , in this way defining a quantity  $n_s$  which characterizes the conditions for the highest statistical significance of detection. We obtain the result shown in Fig. 4.

We notice that for very small signals, very near the threshold, that is  $7 \times 14 = 100$  mK, the maximum  $n_s$  occurs for  $w \approx 0.5$  s and that for large signals it is convenient (as intuitively expected) to take  $w$  as small as possible. Considering that: (i) the sampling time for this data is 0.2908 s, (ii) from Fig. 4, the best

Table 4  
Result of the coincidence search between EXPLORER and NAUTILUS

$T_{e,T}$ max [mK]	# hours in common	$\langle T_{\text{eff}} \rangle$ [mK] Expl	$\langle T_{\text{eff}} \rangle$ [mK] Naut	$n_c$	$\langle n \rangle_{\text{exp}}$	$\langle n \rangle_{\text{th}}$	$p$ %	$p_{\text{exp}}$ %
25	162	12	7	4	1.81	1.80	10	10.25
50	701	16	16	19	10.8	11.1	1.5	1.44
100	1372	23	28	31	24.3	25.2	10.7	10.83

window for signals with energy up to 200 mK (twice the threshold) is  $w = 0.3$  s, we consider it reasonable to take as coincidence window for the EXPLORER and NAUTILUS coincidence search the sampling time of the detector, that is  $w = \pm 0.2908$  s.

As far as the window for the search for coincidences between EXPLORER and NIOBE we are forced to take  $w = \pm 1$  s, because of the uncertainty in the time measurement.

## 6. Coincidences

### 6.1. EXPLORER and NAUTILUS

We have searched for coincidences for EXPLORER and NAUTILUS within a window of  $\pm 0.2908$  seconds for the three data selections discussed above. In each case, we have determined the experimental number  $\langle n \rangle_{\text{exp}}$  of accidentals by counting the coincidences obtained after time shifting the events of one detector with respect to the other: this was done 10000 times, using time shifts from  $-10000$  s to  $+10000$  s in steps of 2 s. The step is larger than the correlation time for the measured data so that the 10000 determinations of the accidental coincidences are independent.

The result of our coincidence analysis is shown in Table 4.

In the third column we have reported the average value of  $T_{\text{eff}}$  for the corresponding hour selection for EXPLORER and in the fourth column for NAUTILUS. In the fifth column we have the number of coincidences at zero delay, in the sixth the number  $\langle n \rangle_{\text{exp}}$  of accidentals computed from the 10000 time shifts, and in the seventh the corresponding expected number of accidentals  $\langle n \rangle_{\text{th}}$  as computed with Eq. (3), where  $t_m$  is the number of common hours and  $N_{\text{expl}}$  and  $N_{\text{naut}}$  are the numbers of events respectively of EXPLORER and NAUTILUS during such hours. In

the last two columns, finally, we report the calculated Poisson probability  $p$  to have  $n_c$  coincidences or more while expecting  $\langle n \rangle_{\text{exp}}$  on average, and the experimental probability  $p_{\text{exp}}$  obtained by counting how many of the 10000 time shifts gave a number of accidentals equal or greater than the number  $n_c$  at zero delay coincidences.

We notice that  $\langle n \rangle_{\text{th}}$  is in very good agreement with  $\langle n \rangle_{\text{exp}}$ , and the calculated Poissonian probability  $p$  (theoretical probability) also agrees well with the experimental probability  $p_{\text{exp}}$ .

The 19 coincidences for the data selection referring to  $T_{\text{eff}} < 50$  mK are listed in Table 5 with the indication of the time difference  $\Delta t$  between the events of the two detector ( $\Delta t = \text{time of EXPLORER} - \text{time of NAUTILUS}$ ) and the energy of the event. The time is counted from 1 January 1994.

It is noted in Table 5 that some coincident event energies recorded by EXPLORER and NAUTILUS differ by more than an order of magnitude. We have discussed earlier that the effect of the noise acts to spread signal energy, so that a relative large range of energies can be expected. This, however, only partially explains the above finding, as the basic reason is the effect of the previously mentioned nonstationary noise. We sometimes have, in fact, periods with duration of a few minutes with relatively high noise, also during hours with  $T_{\text{eff}} < 50$  mK.

These small periods of relative higher noise were not eliminated from the analysis, in order to avoid any deviation from the strict rules established in Section 4.

However, the objection can be raised that coincidences with a very large ratio of the two energies have small chance to have physical meaning and then the question arises of what happens if the search of coincidences eliminates all pairs whose two energies have a ratio outside certain limits. It is clear that this condition cannot be applied only to the coincidences listed in Table 5, because such a condition also affects

Table 5  
List of coincidences for the hours with  $T_{\text{eff}} < 50$  mK

day	hour	min	sec	$\Delta t$	Expl [K]	Naut [K]
868	1	27	48.35	-0.26	0.25	1.13
913	23	44	46.40	0.28	0.83	2.08
951	0	35	30.49	-0.28	2.88	0.12
965	21	28	5.370	-0.14	0.44	17.72
974	13	26	27.93	0.15	0.19	0.75
974	21	35	47.35	0.12	0.07	0.22
989	2	38	49.81	-0.12	1.90	8.23
997	12	40	24.26	-0.24	1.69	0.41
999	21	56	3.930	0.16	1.44	0.66
1001	1	3	48.95	0.16	0.88	0.23
1002	7	32	22.20	0.25	1.38	0.11
1002	22	42	31.35	-0.03	0.99	9.95
1009	21	15	52.87	-0.06	1.53	2.03
1011	18	28	56.83	-0.28	0.81	7.86
1013	5	34	55.88	-0.15	0.08	0.49
1014	2	7	59.76	-0.15	0.11	0.29
1014	3	29	51.05	0.13	0.07	4.14
1018	3	16	12.98	-0.27	0.98	0.46
1028	20	48	58.12	-0.03	3.05	0.29

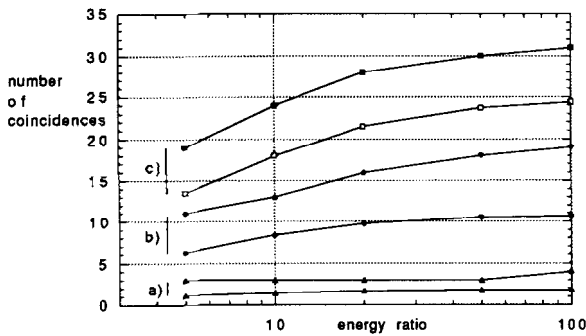


Fig. 5. Real and accidental coincidences versus the veto for the ratio of the energies of the Explorer and Nautilus coincident events. Only coincidences with energy ratio smaller than the value indicated on the abscissa are taken. The pairs (a), (b) and (c) refer to the selected periods with hourly noise  $T_{\text{eff}}$  smaller, respectively, of 25 mK, 50 mK and 100 mK. For each pair of curves the upper one indicates the real coincidences and the lower one the accidentals.

the number of accidental coincidences. We have, then, searched for coincidences applying a veto on the energy ratio and the result is shown in Fig. 5.

In this figure the real and accidental coincidences versus the energy ratio veto for the three cases of the data selection are shown. We note that in all cases a coincidence excess remains for which the probability to occur by chance is between 1.5 and 10%.

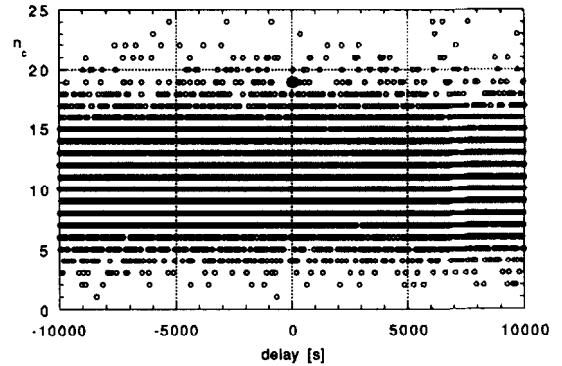


Fig. 6. Delay distribution of the EXPLORER and NAUTILUS coincidences for the 702 hours with noise temperature smaller than 50 mK. The large dot at zero delay indicates the number  $n_c = 19$  of coincidences.

It is important to check that the probability estimation is correct. We checked that, when shifting in time 10 000 times by steps of 2 s, the accidental coincidences are independent of time shift and properly distributed with stationary Poissonian law. This is shown in the following figures for the data selected with hourly averaged  $T_{\text{eff}} < 50$  mK.

In Fig. 6 we give the numbers of coincidences for each one of the 10 000 time delays, including the number  $n_c = 19$  obtained at zero delay. The time distribution appears to be rather uniform.

In Fig. 7 we give the distribution of the accidental coincidences for the 10 000 delays. The continuous line is calculated with the Poisson law with average value 10.8 deduced from Table 4.

Finally we have calculated the autocorrelation of the 10 000 accidentals versus the number of 2 s steps shown in Fig. 6, in order to check that the 10 000 accidental coincidences are independent one from each other. The result of this calculation gives values close to zero for all delays greater than or equal to 2 s.

## 7. EXPLORER and NIOBE

The search for coincidences between EXPLORER and NIOBE in the overlapping period day 180 to 280 of year 1995 according to the above procedures has given the result shown in Table 6. In this cases 1000 time delays were used. The common period of best performance was much larger than in the case of NAUTILUS and EXPLORER. Unfortunately the



Table 6  
Result of the coincidence search between EXPLORER and NIOBE

$T_{\text{eff}} \text{ max [mK]}$	# hours in common	$\langle T_{\text{eff}} \rangle \text{ [mK] expl}$	$\langle T_{\text{eff}} \rangle \text{ [mK] Niobe}$	$n_c$	$\langle n \rangle_{\text{exp}}$	$\langle n \rangle_{\text{th}}$	$p \%$	$p_{\text{exp}} \%$
25	855	11	4	70	85	86	96	95.7
50	1202	13	5	101	119	119	96	95.9
100	1362	15	7	121	134	133	89	87.4

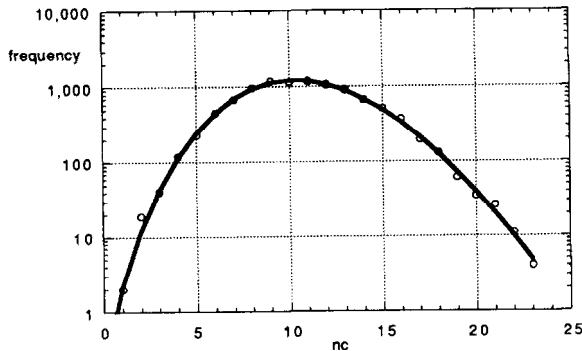


Fig. 7. The continuous line is the Poisson probability distribution (multiplied by the 10 000 trials) with average value of 10.8 multiplied by 10 000. The dots show the experimental frequency distribution for the data shown in Fig. 5.

larger time window substantially increases the number of accidental coincidences by a factor 1/0.29, so that a small excess similar to that observed by EXPLORER and NAUTILUS would not be discernible.

This emphasizes the importance of improving the time resolution and also of using other methods to reduce the accidentals, as we plan to do in further analyses.

## 8. Conclusions

We have searched for coincidences among the three distant detectors, EXPLORER, NAUTILUS and NIOBE, analyzing all the available data and taking care to establish the rules for the statistical analysis before actually performing it. The result for EXPLORER and NAUTILUS is shown in Table 4. An indication for a weak coincidence excess is found. No confirmation from the EXPLORER and NIOBE coincidence search has been found, but in this last case the larger coincidence window increases the number of accidentals by a factor 1/0.29.

In the analysis presented here we have taken extreme care to minimize the number of choices which could influence the result. We realize that some of these a priori choices, in particular as regards the data selection, could be objected on the ground of data quality arguments. For example, instead of considering the hourly noise temperature, we could have selected the data on the basis of the “local” noise behavior, thereby better accounting for the nonstationary noise. We also understand that it is possible to apply additional filters to reduce the background, such as direction filters, filters based on the shaped (or the duration) of the events, or the energy ratio filter which vetoes coincidence events for which the event energies are very different. This last filter must be implemented with care, however, since its implementation depends strongly on the observed pulse energy distribution in each antenna. In addition, when the detector frequencies are different, the implementation of such a filter requires assumptions about the expected spectral characteristics of the signal.

In view of these difficulties we have deferred a more detailed analysis, basically aimed at refining the present findings on more physical bases, until statistically appropriate protocols are established.

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