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Abstract

A search for gamma-ray bursts (GRBs) above 20 TeV within the field of view (1 sr) of the HEGRA AIROBICC Cherenkov array (29°N, 18°W, 2200 m a.s.l.) has been performed using data taken between March 1992 and March 1993. The search is based on an all sky survey on four time scales, 10 seconds, 1 minute, 4 minutes, and 1 hour. No evidence for TeV-emission has been found in the above data sample. Flux upper limits are given. For GRBs detected by BATSE and WATCH a special analysis has been performed. Two partially and two fully contained GRBs in our field of view (FOV) were studied. For GRB 920925c which was fully contained in our FOV, the most significant excess has a probability of $7.7 \cdot 10^{-8}$ (corresponding to 5.4σ) for being caused by a background fluctuation. Correcting this probability with the appropriate trial factor, yields a conservative estimate of 99.6% confidence level (CL) for this excess been related to the GRB. This result is discussed within the framework of the WATCH detection.

1 Introduction

TeV/PeV emission associated with GRBs has been searched for extensively. These studies are motivated by both, the experimental results obtained with the satellite experiments as e.g. EGRET and by theoretical models [1] which predict or least allow for TeV emission to be produced in GRBs. So far none these searches have revealed any convincing evidence for VHE emission [2, 3, 4], although recently some tentative positive evidence has been found in this energy range [5, 6].

Up to now five BATSE GRBs have been detected by EGRET with photons of energies up to 18 GeV [7]. Those GRBs are among the most intense ones recorded by BATSE in the FOV of EGRET, so observations are compatible with the hypothesis that all GRBs emit GeV photons but only the strongest ones are above the EGRET sensitivity. A simple power law extrapolation of the Superbowl GRB spectrum [8] predicts that ~20 photons above 20 TeV should be

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observed with the AIROBICC array within 25 seconds while expecting only 0.1 background events. This would lead to a highly significant detection by several other experiments currently operated (Cherenkov telescopes, EAS arrays, see [2, 3, 4]). The previous extrapolation assumes no source-intrinsic cutoffs and no attenuation through interaction with the infrared background, as expected for cosmological sources with redshift larger than 0.1. Another interesting feature of strong GRBs is that their high energy emission can be delayed and have longer durations than the keV-MeV emission [7]. These ideas trigger searches for counterparts at times and with durations somewhat independent from those given by the space detectors at lower energies, specially considering that the latter could miss GRBs out of their FOV or with a very hard spectrum, as already has been suggested [9].

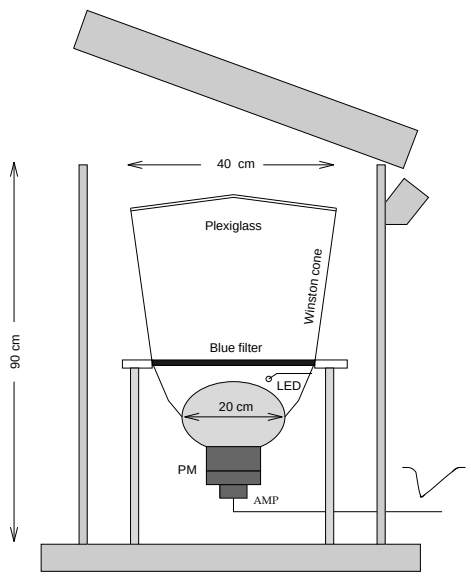

Figure 1: Scheme of an AIROBICC station.

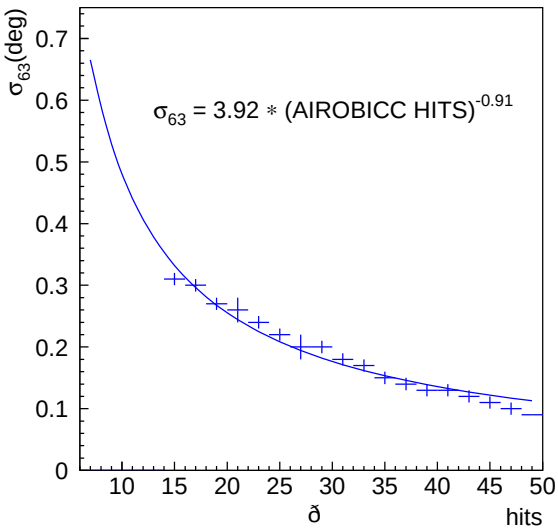

Figure 2: Angular resolution of AIROBICC as a function of the number of triggered stations. σ_{63} is defined as the angular distance which contains 63% of the events from a point source.

2 The AIROBICC array

The AIROBICC array is part of the cosmic ray (CR) detector complex HEGRA located at the Roque de los Muchachos on the Canary Island La Palma (28.75° N, 17.89° W, 2240 m a.s.l.). It is an array of 7x7 stations (now been enlarged to 8x8 plus a subarray of 4x4 to increase detector density in the center) with a regular grid spacing of 30 m, thus covering more than 32000 m^2. Each station consists of a 40 cm diameter reflecting cone which focuses the incoming light onto a fast 20 cm diameter photomultiplier tube (PMT) (see Fig. 1). The set is placed inside a protective hut with a lid which can be opened through remote control. The PMT is covered with a blue filter (λ =300-480 nm) to improve signal to noise ratio (SNR). The output from the PMT is amplified in the hut and sent through a 150 m long cable to the central electronics where it is split into two channels, one which goes directly to an ADC (low gain channel), and the other one which is further amplified and sent to a constant fraction discriminator (CFD). The CFD is set to a 5σ equivalent level of the night sky background (NSB) fluctuations. Whenever six or

more AIROBICC stations exceed the CFD threshold within 200 ns, a trigger is produced which starts the TDC and ADC modules. The digital output from the CFD stops the TDC channel and the analog output is sent to an ADC (high gain channel) through a linear gate which is opened only for 30 ns to remove NSB noise. Both signals are properly delayed to account for trigger delay due to the electronics. The ADC and TDC modules are read out with a computer which stores the data on magnetic tapes together with other information like time of the event, calibration data and so on. Calibrations are performed every 20 minutes (last for $\sim$90 seconds) to measure the relative delay between stations, the response of the TDC and the ADC pedestals. The mean dead time after an event is recorded is $\sim$8 ms. Detailed descriptions of AIROBICC and the rest of the HEGRA complex can be found in [10, 11, 12].
The ADC signals (AIROBICC + scintillator array) are used to locate the EAS core position with a typical error $\leq$18 m. The Cherenkov light front is fitted by a cone to determine the arrival direction of the incident CR. The angular resolution is 0.29° when 12 stations are activated (standard cut) and it continuously decreases with increasing number of triggered huts (see Fig. 2). The absolute pointing accuracy has been estimated through comparison with the first HEGRA Cherenkov telescope to be better than 0.2° [10]. The FOV, which is limited by the acceptance of the Wiston cone, is 1 sr and the trigger rate is $\sim$20 Hz. The energy threshold is estimated to be $\sim$16(25) TeV for γs and $\sim$29(37) TeV for hadrons with zenith angle $\theta \leq 20^\circ (20^\circ < \theta < 35^\circ)$ using flux and Monte Carlo studies [13]. The price one has to pay for the advantages of the Cherenkov technique (lower energy threshold, better angular resolution) is that observations are restricted to moonless clear nights ($\sim$10% duty cycle).

3 Analysis

The data analyzed in this work were taken during the first year of operation of AIROBICC, between March 1992 and March 1993. The mean trigger rate in this period was $\sim$16 Hz. The sample contains $\sim 4 \cdot 10^7$ events ($\sim$800 hours) and after requiring a successful arrival direction reconstruction of those showers with $\geq$7 fired stations, about $\sim 2.5 \cdot 10^7$ events ($\sim$60%) survive. It has been shown that due to the low counting statistics encountered when dealing with transient phenomena, one has to keep as much events as possible; and so we do not apply the standard cut in the number of fired huts. The angular resolution is then $\sim 0.6^\circ$ (see Fig. 2).
The analysis is based on a binned (in time and in space) all-sky search. We define an ON window or signal window and an OFF window or background window where events are counted for a certain time interval. The search strategy considers each event as being in the middle of a burst, so for every single event in the data sample we take a pair of ON-OFF windows whose time interval is centered at the time of the event. The ON window is a circle of 0.7° radius centered at the position of the event and the OFF window is an annulus of 1.5° and 10.0° radii concentric to the ON window. There is always one event inside the ON window and to reduce this bias it is excluded (not counted). The size of the ON window is chosen such that it maximizes the SNR according to our resolution (see above) as described in [14] and it is expected to contain 75% of the events for a point source. While the size of the OFF window is taken as large as possible to increase statistics, its limit is due to the systematic error introduced because of the non-linear dependence of the counting rate on declination [14]. We performed a Monte Carlo (MC) calculation to find the largest radius that keeps the systematic error much lower than the statistical error due to the low counting rate. Results are shown in Fig. 3. The time intervals we chose are 10 seconds, 1 minute and 4 minutes which cover the usual long duration GRBs. The dead time and low counting rate do not allow for searches with much shorter duration. The employed procedure has the advantage of being very sensitive but

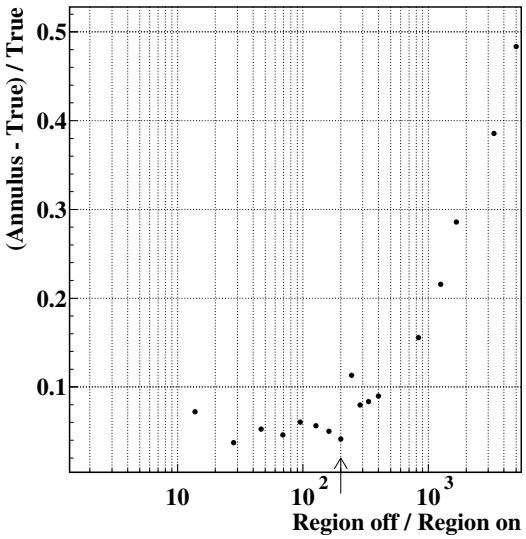

Figure 3: Systematic error in the estimation of the background with the annulus method as a function of the ratio of the solid angles of the OFF and ON windows. The ON window is a fixed circle of 0.7° radius and the OFF window is an annulus of fixed 1.5° inner radius and variable outer radius. The time interval is 4 minutes which is expected to have the highest systematic error. The points are the average over several hundred windows. The sample used for this calculation consists of MC events generated as described in the text. The systematic error has a constant value of less than 5% up to a certain size of the OFF window, from which it grows very quickly. The arrow points to the value used in this work. This error has to be balanced with the statistical error which is at best 20%. Note that the systematic error is positive, i.e. it is conservative.

also quite time consuming. The time needed for the analysis grows as the square of the length of the time window. So in order to look for TeV-emission on longer time scales, a less sensitive search with a 1 hour time window and a classical non-overlapping rectangular grid of 0.5°x0.5° in celestial coordinates has been carried out. In this case the background is estimated by means of a MC method as described in [14]. For every real event we generate 100 MC events with random directions following the acceptance function of AIROBICC (obtained with the events of a whole run, therefore a different run implies a different acceptance function).
To obtain the significance of a hypothetical signal we use the probability distribution given in [14] which is appropriate for low statistics (Poissonian regime):

$$P(\geq N_{ON} \mid N_{OFF}) = 1 - \sum_{n_{ON}=0}^{N_{ON}-1} \frac{\alpha^{N_{ON}}}{(1+\alpha)^{n_{ON}+N_{OFF}+1}} \frac{(n_{ON}+N_{OFF})!}{n_{ON}!\ N_{OFF}!}$$

where N_{ON} and N_{OFF} are the number of events in the source and background windows respectively. In case of random distribution of the events (i.e., no GRBs), a cumulative histogram of -$\log_{10}P$ for all the windows should follow a straight line with slope of -1, which cuts the Y-axis at the height of the total number of windows (trials). A strong GRB or several weaker GRBs should therefore appear as a deviation from the line. The significance of a deviation can be calculated knowing that every bin theoretically follows a binomial distribution. Actually this approach is only an approximation because the probability distribution is discrete and there is

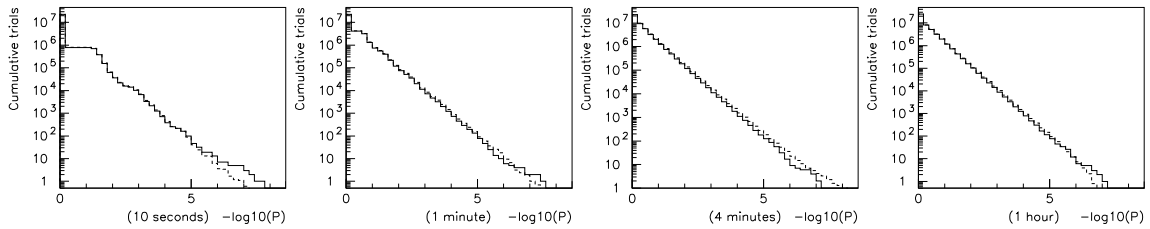

Figure 4: Cumulative trials vs. probability in the all sky search. The time scale is indicated in brackets. Continuous line is real data and dashed line is the result (normalized) over a MC sample 10 (20 in the 1 hour scale) times greater than the real one. Deviations are not significant, all have $p \gtrsim 0.1$.

an oversampling (i.e., search windows overlap and thus trials are not independent) in the search with short time windows. Therefore we estimate the significance repeating the search over a MC sample which is 10 times larger than the real one in the case of the short time windows and 20 times larger in the case of the 1 hour search window.

4 Results

The results for the all sky search are shown in Fig. 4. It presents the cumulative number of trials (search windows) against -$\log_{10}P$ for the all sky search with the four time scales we have used. The results for the MC sample are also shown. Obviously, the experimental data set is consistent with MC expectations. All deviations have a probability greater than $\sim$0.1. This result allows us to place an upper limit on the flux of any hypothetical GRB which may have occurred anywhere in the sky during our observations. Depending on the declination band the resulting upper limit corresponds to two energy thresholds for every time scale.
Assuming the same spectral index for the source and the CR flux and a steady emission during the time interval, we can estimate the integral flux upper limit with the formula (see [15])

$$F_{UL}(E > E_{th_\gamma}) = \frac{N_{UL}\Omega_{ON}}{\alpha(N_{OFF}+1)\beta} F_{CR}(E > E_{th_{had}})$$

where F_{UL} is the 90% CL upper limit on the integral flux, E_{th_γ} and $E_{th_{had}}$ are the energy thresholds for γ and hadrons respectively, N_{UL} is the 90% CL upper limit on the excess of events in the source window calculated as in [16], Ω_{ON} is the solid angle of the source window, α is the ratio between the source and background windows and β is the fraction of source events expected to fall in the source window. F_{CR} is the known CR integral flux and is taken as $1.8 \cdot 10^{-5} E(\mathrm{TeV})^{-1.76}$ cm^{-2} s^{-1} sr^{-1} [15, 17]. We applied this calculation to all ON-OFF windows and determined the highest values. The resulting flux upper limits are listed in Table 1. Its uncertainties are estimated to be $\sim$40%.
Additional constraints on the data sample as e.g. imposed by the burst detections of BATSE, WATCH and other GRB detectors in space, can serve as a tool to reduce the full data set and thus the expected statistical fluctuations. Hence, the sensitivity for weaker GRBs is enhanced. We therefore searched in the BATSE 3B catalog [18] and in the first WATCH catalog [19] for triggers which were within the FOV of AIROBICC at the time they occurred or up to 2 hours later (because of possible delayed emission). They are shown in Table 2. The sample is then

Table 1: 90% confidence level upper limits on the integral flux of any hypothetical GRB occurred in our data sample. They are tabulated depending on the time window and the declination band. Uncertainties are ∼40%.

Time scale	10 sec	1 min	4 min	1 hour
$F_{UL}(E>16\text{TeV})$ (cm^{-2} s^{-1}) $(9^\circ < \delta < 49^\circ)$	$4.5{\cdot}10^{-8}$	$3.5{\cdot}10^{-8}$	$2.5{\cdot}10^{-8}$	$3.5{\cdot}10^{-9}$
$F_{UL}(E>25\text{TeV})$ (cm^{-2} s^{-1}) $(-6^\circ < \delta < 9^\circ,\ 49^\circ < \delta < 64^\circ)$	$2.8{\cdot}10^{-8}$	$2.2{\cdot}10^{-8}$	$1.6{\cdot}10^{-8}$	$3.2{\cdot}10^{-9}$

reduced to events within $\pm 10^\circ$ and ± 3 minutes around the GRB location. We also looked for a delayed component for two hours after the initial trigger. The size of the search region in celestial coordinates has been chosen large enough to account for the uncertainties of the GRB location. The length in time of the search interval (for coincident and delayed emission) has been taken according to the observations in the GeV energy range [7].
The most significant excess in the full data set was found almost in coincidence with the WATCH GRB 920925c but 9° away from it. This observation is discussed in the next section. The results for the rest of the GRBs are shown in Fig. 5. It presents the cumulative number of trials against -$\log_{10}P$ for the four time scales used in the two search strategies (coincident and delayed emission). The approximated expected behavior is shown as a dashed line. No significant deviation is seen. This again allows us to place an upper limit on the integral flux of these GRBs. However, we do so only for GRB 920525b because it is the only one completely covered by the data set among the three GRBs. The upper limits on the integral flux are calculated at 90% CL in the same way as shown before. The results for the coincident and delayed emission with the four time scales used here are shown in Table 3. Its uncertainties are estimated to be ∼40%.

Table 2: List of GRBs observed in coincidence with satellites. θ is the zenith angle of the GRB at the AIROBICC site.

Date	Time (UTC)	α (J2000)	δ (J2000)	Observer	θ at trigger	θ 2^h later	Coverage
25 MAY 92	00:41:44	$15^h16^m50^s$	37.3°	BATSE	10.0°	31.4°	Full
25 SEP 92	22:46:16	$22^h04^m19^s$	24.2°	WATCH	5.1°	25.1°	Full
18 NOV 92	22:11:44	$23^h21^m48^s$	50.3°	BATSE	27.6°	44.9°	Partial
23 JAN 93	18:45:21	$04^h01^m34^s$	38.3°	BATSE	29.6°	10.0°	Partial

5 Observational results for WATCH GRB 920925c

As it was mentioned in the previous section, the search for emission from GRB 920925c had a surprising result. A very large excess was found in the search for emission in coincidence with the WATCH trigger on all short time scales. No excess has been found neither in the search for delayed emission nor in the 1 hour time window. The results for the four time scales, in the two search modes (coincident and delayed emission), are shown in Fig. 6. Again the cumulative number of trials is plotted as a function of -$\log_{10}P$ and the dashed line shows an approximation

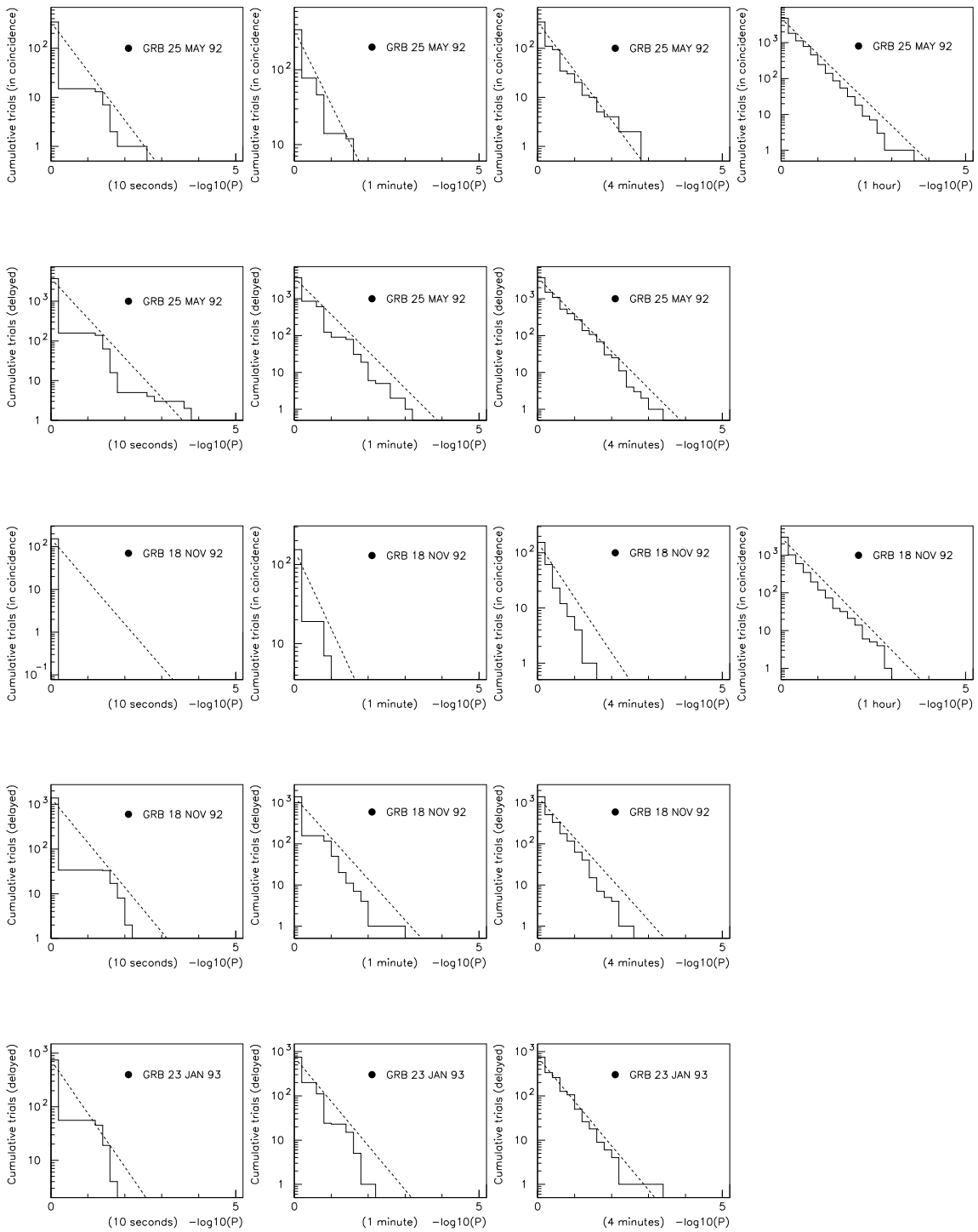

Figure 5: Cumulative trials vs. probability in the search for the GRBs 25MAY92, 18NOV92 and 23JAN93. We show the results of the search for coincident and delayed emission. For GRB 23JAN93 only the result for delayed emission is shown because AIROBICC started more than one hour after the burst trigger. The dashed line shows the approximated expected behavior. No significant deviation appears.

Table 3: 90% confidence level upper limits on the integral flux of GRB 920525b in different time scales and for two scenarios: coincident and delayed emission. Uncertainties are $\sim$40%.

Time scale	10 sec	1 min	4 min	1 hour
$F_{UL}(E >16\text{TeV})$ (cm^{-2} s^{-1}) (in coincidence, $\pm$3 min)	$8.9{\cdot}10^{-9}$	$8.9{\cdot}10^{-10}$	$3.2{\cdot}10^{-10}$	$4.0{\cdot}10^{-11}$
$F_{UL}(E >16\text{TeV})$ (cm^{-2} s^{-1}) (delayed, up to 2^h later)	$1.3{\cdot}10^{-8}$	$1.4{\cdot}10^{-9}$	$3.2{\cdot}10^{-10}$	———

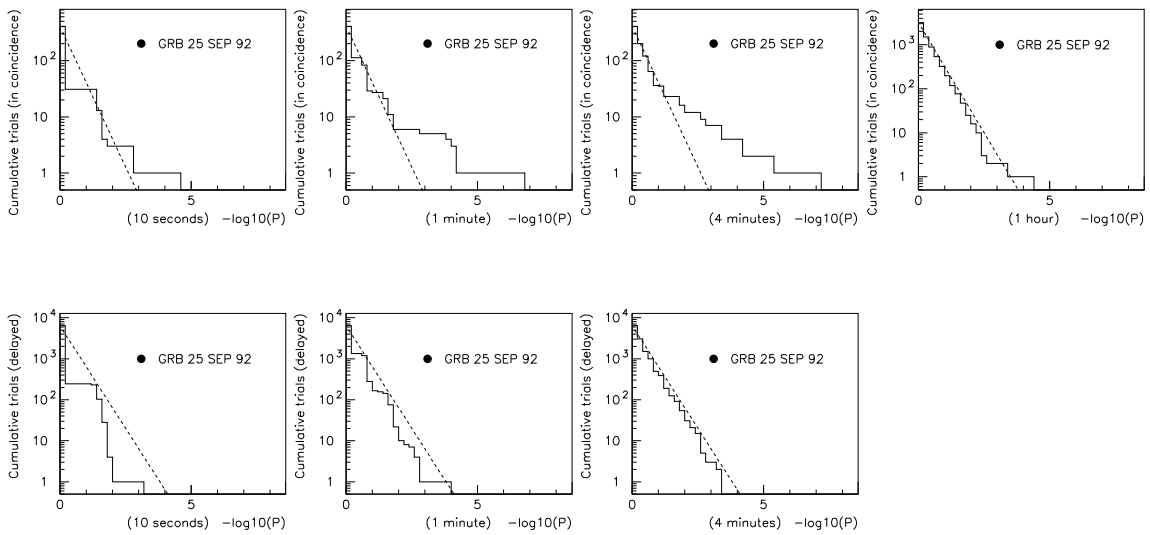

Figure 6: Cumulative trials vs. probability in the search for GRB 920925c. We show the results of the search for coincident and delayed emission. The dashed line shows the approximated expected behavior. A significant deviation appears in some of the plots.

of the expected behavior. In this case significant deviations from the expectations are observed, specially on the 4 minute time scale (coincident emission), which shows a deviation with a chance probability $< 10^{-4}$.

The search interval with the smallest chance probability (4 minutes time scale, coincident emission) is centered at $\alpha = 21^h38^m24^s$, $\delta = 16.8^\circ$ (J2000) and UT = 22:45:21. Therefore it precedes the WATCH trigger by less than one minute and is about 9° away from the WATCH localization. For this search interval we observe 11 events in 4 minutes while 0.93 events are expected. The chance probability for the background to yield such an excess, computed according to the formula shown above, is $7.7{\cdot}10^{-8}$ and the Li and Ma significance [20] is 5.4σ (in both cases we take into account only 10 events inside the search interval, see above). This is the most significant excess seen in the whole data sample (compare Fig. 6 with Fig. 4). Correcting this probability with a trial factor due to the search for four GRBs on several time scales and in a large solid angle region, yields a final probability of $3.7{\cdot}10^{-3}$, i.e. the CL that this excess is related to the WATCH burst is 99.6%. This is a conservative estimate because the fact that not all the trials

are independent was not taken into account. The data registered with the HEGRA scintillator array does not show any excess, which may be due to its higher energy threshold and worse angular resolution.
Assuming that this excess is due to high energy emission we can calculate the integral flux in the same way as the upper limits, but replacing N_{UL} with N_{ON}. In this case the mean integral flux above 16 TeV during the 4 minutes window is $(9 \pm 4) \cdot 10^{-10}$ cm^{-2} s^{-1}.
The burst had a duration of $\sim$5 minutes exhibiting two main peaks. It was observed by WATCH and ULYSSES, thus reducing the possible locations to an IPN annulus [21]. The IPN ring is tangent to the WATCH 1σ error circle and is 3° away from the excess observed with the AIROBICC array, see Fig. 7.
Spectral data from WATCH in the interval 6-100 keV can be fitted by a power law spectrum. The fit yields a spectral index of 2.5 ± 0.2 which, if naively extrapolated, does not predict any TeV flux detectable by AIROBICC. However, the TeV spectrum may differ significantly from what one expects from the 100 keV extrapolation. Furthermore, the hypothetical emission at TeV energies precedes the WATCH observations and may therefore be due to another spectral component.

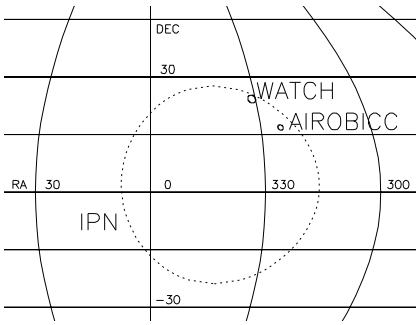

Figure 7: Map with the situation of the WATCH GRB 920925c and the IPN ring. The location of the excess seen by AIROBICC nearly coincident in time with WATCH is also shown.

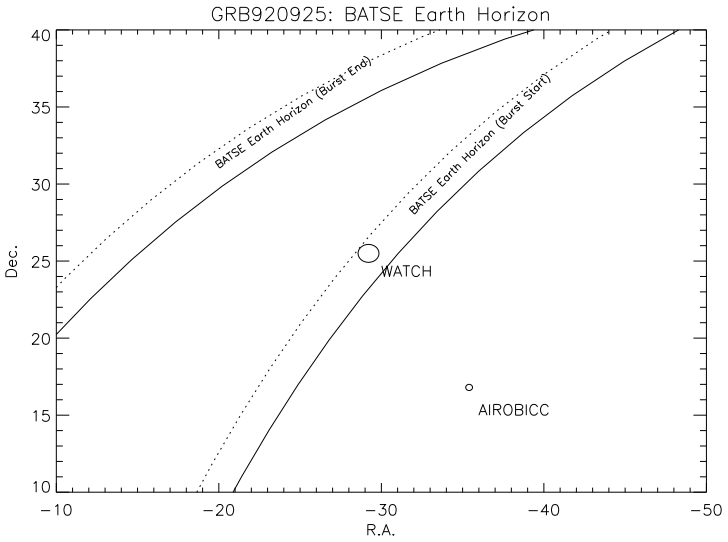

Figure 8: Map showing the sky as seen by BATSE at the time and position of the WATCH GRB 920925c. The location of the excess seen by AIROBICC nearly coincident in time with WATCH is also shown.

6 Discussion

In order to add new clues that may clarify whether the excess recorded with AIROBICC is related to GRB 920925c, the BATSE team [22] investigated the reason why BATSE did not see this burst. There are two reasons why BATSE may have missed the burst: either the burst was not strong enough to overwrite a previous trigger or the Earth (or the Moon) occulted the source. The BATSE team kindly provided us with a map of the sky in the region and at the moment of GRB 920925c as seen by BATSE (see Fig. 8) [22]. It shows that the AIROBICC

localization was completely occulted by the Earth throughout the whole burst. Therefore the AIROBICC observation is compatible with BATSE not seeing the bursts. The WATCH position is on the Earth's limb at the beginning of the burst and is then occulted about one minute later. Whether the first peak of the burst (which is within the first minute after the initial trigger) was able to trigger BATSE, seems to be unimportant as long as the Earth's atmosphere was interposed between BATSE and the WATCH localization even at the start of the burst. So the position given by WATCH is also consistent with the non-detection of the GRB with BATSE.
A cross check of the positions of bursts given by BATSE, WATCH and IPN since 1991 to 1994 reveals some events with disagreement at a level of 5σ or even more, so an error in the WATCH localization cannot be discarded (if the error is due to timing it would also affect the IPN location estimate). If one wishes to interpret the angular and time separation among WATCH, IPN and AIROBICC detections in terms of parallax effects or superluminal motion, the source should not be more distant than about 100 AU.
At the moment it is not possible to decide on the nature of the excess recorded with AIROBICC. Note that this GRB had a large fluence at keV energies, but was not very intense. The GRB occurred under a small zenith angle (12°) and could thus be studied with a low energy threshold of the AIROBICC array. The energy distribution of the events of the excess is below the energy distribution of background events on the 2.5σ CL. The excess appears to be characterized by a steeper spectrum than the spectrum of the background of charged cosmic rays (differential index 2.76). The latter could be indicative of a cutoff in the GRB spectrum due to absorption of the TeV photons by the intergalactic infrared background [23, 24, 25]. On the other hand the angular separation between the AIROBICC localization and the WATCH and IPN location is significant.

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