# The GRAAL experiment

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GRAAL uses 63 heliostats of the CESA-I field at the Plataforma Solar de Almeria for the collection of the Cherenkov light generated by air-showers. The energy threshold for $\gamma$ rays is 250$\pm$110 GeV. Signal from the Crab pulsar with a significance of 4.5 $\sigma$ has been found. Because of the restricted field of view of the optical system $\gamma$/hadron separation turns out to be very difficult.

## 1. INTRODUCTION

Observation of atmospheric Cherenkov radiation is presently the most effective way to detect cosmic $\gamma$-rays of very-high energy. The energy threshold of this technique is limited by the sensitivity for the detection of the Cherenkov pulses over the Poissonian fluctuations of the night sky background NSB light. This sensitivity grows (apart from other parameters) with the square root of the area of the Cherenkov light collector. In 1982 Danaher et al. [1] proposed to use the mirrors of a solar power plant (heliostats) as primary collector of the atmospheric Cherenkov light. Presently several experiments are using this technique (CELESTE [2] in the French Pyrenees, Solar2 [3] near Barstow (CA) and STACEE [4] at the NSTTF, Albuquerque (NM)). In these experiments the Cherenkov light collected by every heliostat is focused into an individual PMT. On the other hand, the GRAAL experiment [5] follows a different technique which will be next described along with some observation results.

## 2. THE *GRAAL* TELESCOPE

GRAAL uses the heliostat field CESA-I which is a facility of the Plataforma Solar de Almeria PSA (the largest solar-thermal energy research center in Europe) located near the town of Tabernas (Almeria, Spain) (37.09 N, 2.36 W). at an altitude of 505 m a.s.l. CESA-I comprises of about 300 mirrors (37.9 m$^2$ each) to the North of a central tower. GRAAL uses 63 of them with a total collecting area of about 2500 m$^2$. Each heliostat is individually steerable with stepping motors via a central PC. A control program was developed that allowed to perform the special tracking needed for Cherenkov astronomy. The so-called convergent view technique was used. The mirrors (in the general direction of the source) point to a region at an atmospheric depth of 230 gcm$^2$ where the Cherenkov light from cosmic $\gamma$ rays are expected to be generated.

The GRAAL experiment follows a different technique as compared with the others solar array telescopes. Cherenkov light from four groups of heliostats (13 - 18 heliostats per group) is directed onto four non-imaging light concentrators (truncated Winston cones) of 1.08 m diameter and 2,0 m length. These cones are housed at the 70 m level of the central tower and they are directed onto a point at ground in such a way that each one collects the light from the heliostats within its opening angle (10 deg.) to a six-stages 8 inches PMT optimized for operation under high background light levels (see figure 1). The final FWHM of the Cherenkov pulses after the amplifiers is of about 3.6 ns.

Two independent triggers have been used. The so-called “sequence trigger” is fired if a pulse train with a time structure compatible with a Cherenkov front incoming from the source direction is detected. After a signal above 30 mV a gate of 40 ns length is opened after a delay of 20 ns. If a third signal is detected in this second

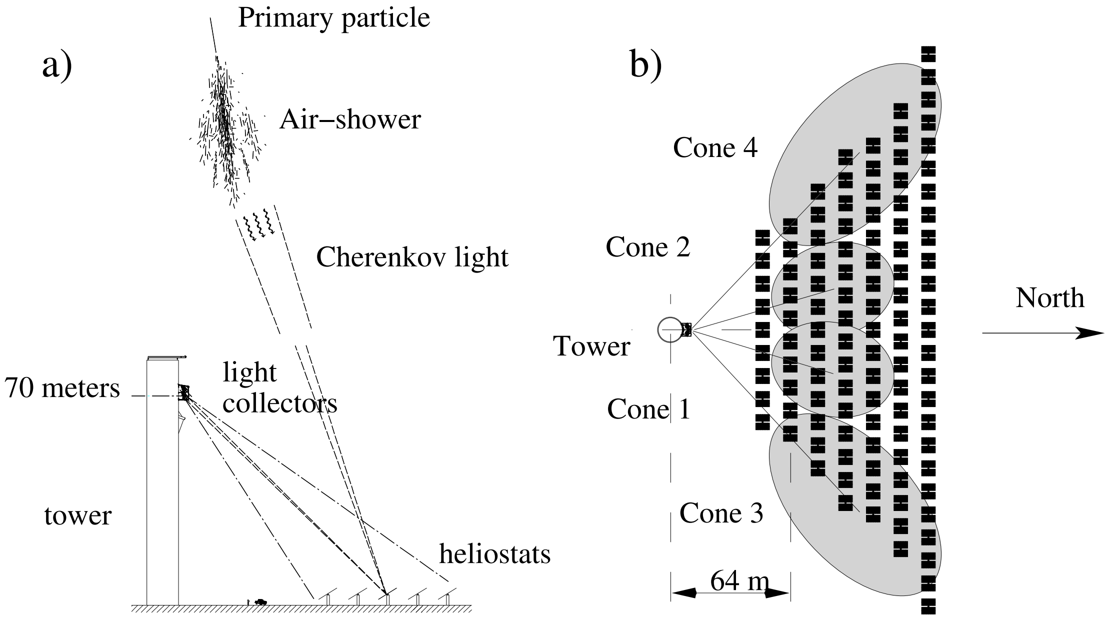


Figure 1. Scheme of the experimental setup. The Cherenkov light of an air shower (not to scale respect to the field) is focused by the heliostats onto the concentrators at the 70 m level of the central tower (a). Figure b) shows the detection geometry seen from above. The squares are the heliostats of GRAAL. Each concentrator sees the light from the heliostats within the corresponding ellipse.

gate an event trigger gate of 200 ns is opened. If the first and second cone have a coincident event trigger the final event trigger is formed. In addition the so-called "charge-trigger" is used. This trigger looks for an integrated charge excess in the PMTs compatible with an event. An amplifier integrates the signal with an exponential response of 100 (200) ns for cones 1 + 2 (3 + 4). If the integrated signal surpasses a certain level within a coincidence gate of 200 ns the trigger fires. Both triggers are in a logical OR mode. While the sequence trigger depends sensitively on the incoming direction of the shower, but it is basically insensitive on the NSB, the charge trigger is more dependent on NSB but independent on shower direction.

All four pulse trains are registered in one digital oscilloscope 1 GHz bandwith (figure 2). The scope is read out in sequence mode into a PC with a dead time below 10% for a trigger rate which was tipically of 2 - 3 Hz.

All operations (opening the door of the hut in the tower, high voltage control, tracking the heliostats,..) are under remote control via the Internet. Various environmental parameters (humidity, ambient light, wind speed, trigger rate,...) are checked. Under any indication of some malfunction the physicist on shift is phoned by the PC. All parameters and web camera images can then be checked remotely.

The experiments CELESTE, Solar2 and STACEE follow the basic idea of Tümer [6], that is, the Cherenkov light of every heliostat is focused by a secondary optics into a single PMT. The major differences between this technique and that used in GRAAL -which collects the light from groups of heliostats in a Winston cone onto a single PMT- are the following. In the first place the NSB is higher in GRAAL roughly by the number of heliostats viewed by one cone. The typical background of GRAAL is of about 8-10 p.e./ns as compared with the 0.7 p.e./ns for the other technique. For the same mirror area this results in a hardware energy threshold of GRAAL of about four times higher. On the other hand GRAAL is much more simple leading to savings by about a factor of 5-10 in hardware costs. Since only four channels are used, automatization and remote control is feasible leading to comparable savings in operation costs. In addition the small number of channels allows a time resolution of 0.5 ns/bin. Finally in the GRAAL approach it is impossible to avoid peak overlapping at certain pointing directions, reducing the usable information in the reconstruction.

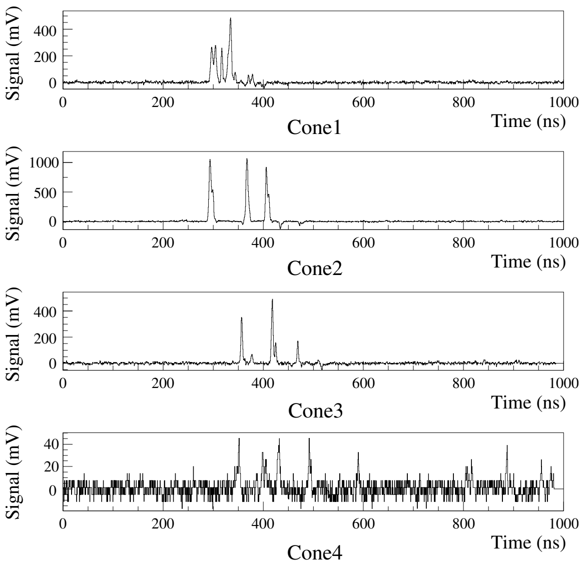


Figure 2. The signal amplitude after amplification recorded in all four cones versus time. Each peak corresponds to the Cherenkov-light flash of the shower reflected by a different heliostat.

## 3. EVENT RECONSTRUCTION

The different arrival times of the signals from individual heliostats were used to reconstruct the timing shower front of individual events. The expected arrival times for all heliostats in each cone are calculated for a 5 deg.$\times$ 5 deg. grid centered at the pointing direction (in fact with 1 degree offset to avoid bias towards "correct pointing"). For this calculation, a point-like shower maximum at 230 g/cm$^2$ depth in the pointing direction was assumed. The shower core (i.e. the intersection of the shower axis with the ground) was assumed located at the geometrical center of the field. For each individual event the reconstructed direction is the one yielding the smallest value of $\mathrm{lsq_t^2}$ defined by

$$\mathrm{lsq_t^2} = \sum_i (\Delta \mathrm{t_i})^2 \tag{1}$$

where $\Delta t_i$ is the difference corresponding to the heliostat $i$ between the measured arrival time and the nearest expected time from the library. Spurious pulses induced by the NSB, after pulsing in the PMTs or due to cross talk between the subfields sometimes occur. These pulses do not fit into the correct timing pattern and consequently they would bias the fit. For this reason up to 5 peaks with a difference $\Delta t_i$ above 5 ns were allowed to be excluded from the fit. Figure 3 shows projections of reconstructed directions in zenith and azimuth angle both for ON and OFF source directions for a data sample of 32 hours on the Crab pulsar taken in the season 99/00. As can be seen in the figure these distributions follow a gaussian profile over a "plateau" extending to large off-axis angle which corresponds to systematically misreconstructed directions. This background was used in later analysis to normalise ON and OFF rates. The distribution of reconstructed directions (excluding the "plateau") gives an angular resolution $\sigma_{63}$ of 0.7 deg. On the other hand the gaussian profile is always centered in the "real" pointing direction within 0.05 deg. showing that the fitting procedure is not dependent on "assumed" pointing direction.

## 4. MONTE CARLO SIMULATION

Proton and $\gamma$-induced showers have been simulated with the MC package CORSIKA 5.20 [8]. A detector MC simulated the reflection of the Cherenkov photons by the heliostat mirrors into the cones and the further processing of the signals in the PMTs and electronics. The simulation of the trigger provides predictions on the effective area as a function of primary energy for both protons and $\gamma$-rays. These functions have allowed to calculate the energy threshold for $\gamma$-rays which is of $250 \pm 110$ GeV ($300 \pm 130$ GeV) at 15 deg. (30 deg.) zenith angle. Also they have been used for the calculation of the expected trigger rates. For the proton background it turns out to be around 4.0 Hz in good agreement with experimental data. Other relevant experimental parameters are compared with the MC predictions showing a good agreement [5,7]

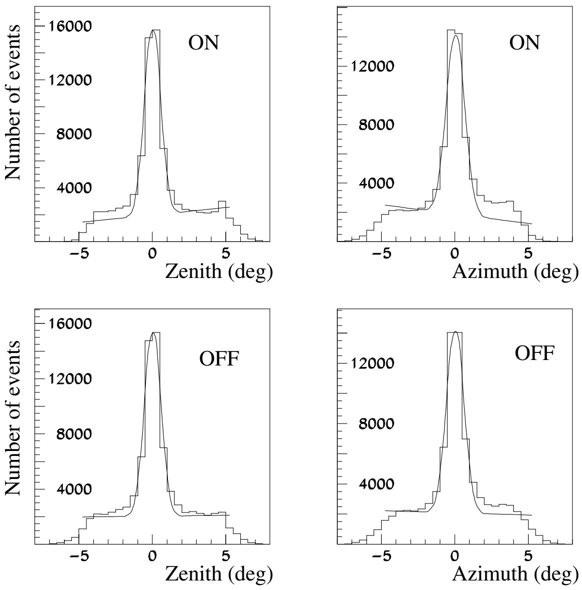


Figure 3. Projections of the number of showers as a function of direction as reconstructed from the timing data for both ON-source (upper panels) and OFF-source (lower panels) corresponding to 32 hours of the Crab pulsar observation in the season 99/00.

## 5. RESULTS ON THE CRAB PULSAR

The data sample in the period Sep.99 - Sep.00 has shown an excess in the Crab pulsar direction. Only data surpassing strict "meteorological cuts" were used (around a 22%). The main problem in all experiments attempting to detect an excess in the total rate due to $\gamma$-rays is the unavoidable variations in the NSB rates in the ON and OFF periods. In our case it has been solved by using the information of the number of events reconstructed with directions deviating more than 2 deg. from the source $(\mathrm{ON,OFF})_{out}$ ("misreconstructed"). A normalized excess has been calculated as

$$\mathrm{EXCESS_n} = \mathrm{ON_{in}} - \mathrm{OFF_{in}} \left(\frac{\mathrm{ON}}{\mathrm{OFF}}\right)_{\mathrm{out}} \tag{2}$$

where $(\mathrm{ON},\mathrm{OFF})_{\mathrm{in}}$ stand for the number of events within 0.7 deg. from the source. Using the results shown in figure 3 it has been found a value of $\mathrm{EXCESS}_n = 737 \pm 165$ events corresponding to a 4.5 $\sigma$ excess and a mean rate of 1.7 events/min. Details on the corresponding flux calculation can be found elsewhere [9].

## 6. REJECTION OF HADRONIC BACKGROUND

The sensitivity of the telescope would increase significantly by an efficient rejection of the background events due to cosmic rays. In principle the solar plant technique allows an accurate determination of both the spatial distribution of the Cherenkov light reaching the ground and the time structure of the Cherenkov front. As is well known, proton induced showers show higher fluctuations than $\gamma$-ray showers in both features and thus in principle $\gamma$/proton separation would be feasible with this technique.

In the solar plant technique the field of view of the detectors is limited to a value of about 0.6 degrees in order to minimize the NSB contribution. With such a field of view a heliostat located near the shower axis is able to observe completely a $\gamma$-ray induced shower. However, heliostats far from the axis would reflect a small fraction of the light reaching the ground because the lateral spread of the shower at its maximum development is significantly smaller than the size of the heliostat field.

Although this problem can be partly solved by operating in the convergent view configuration, unfortunately the restricted field of view significantly diminishes the differences of both spatial and time features of the Cherenkov front making the background rejection very difficult [**?**, Arq01]

## 7. CONCLUSIONS

The GRAAL experiment has been taking data under remote control with an energy threshold for $\gamma$-rays around 250 GeV. Emission of $\gamma$-rays from the Crab pulsar has been detected with a significance of 4.5 $\sigma$. The problem of possible differences in NSB for the ON - OFF periods have been solved by an appropriate normalization using the number of "misreconstructed" events.

In general, the capital costs of an experiment using an existing solar power plant is much lower than that of a comparable dedicated telescope. A particular advantage of GRAAL is its great simplicity which makes remote control feasible leading to further saving in operation costs.

An efficient rejection of the hadronic background would increase significantly the sensitivity of this technique. Unfortunately, the restricted field of view of the heliostats tends to significantly diminish the differences making $\gamma$/proton separation very difficult.

## 8. ACKNOWLEDGMENTS

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