The Mini-GRAAL Project

F.Arqueros[a], D.M.Borque[a], E.F.Camacho[b], F.J.Garcia-Martin[b], H.-J.Gebauer[c], R.Plaga[c1], and G.Weinrebe[d2]

[a] *Facultad de Ciencias Fisicas, Universidad Complutense, E-28040 Madrid, Spain*
[b] *Escuela Superior de Ingenieros, Universidad de Sevilla, E-41012 Sevilla, Spain*
[c] *Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany*
[d] *DLR Hauptabteilung MD-PSA, Plataforma Solar de Almeria, E-04080 Almeria, Spain*

Abstract

Mini-GRAAL (Gamma Ray Astronomy at ALmeria) is an experiment using a heliostat field at the Plataforma Solar de Almeria, located in the Spanish Sierra Nevada, to collect Čerenkov light from air showers. We use the CESA-1 heliostat field that consists of 300 heliostats. Each heliostat has 40 m^2 mirror area and an optical beam quality of about 0.2 ^{o}. The large mirror collection area of this heliostat field allows to reach an energy threshold below 100 GeV in the detection of high-energy gamma rays. Mini-GRAAL aims to use about 70 heliostats using 4 non-imaging light concentrators.
The results of two measurement periods in 1996/97 are described. In these periods only 2 concentrators and a total of 27 heliostats (1069 m^2 collection area) were used. A total of 73000 air-shower events were registered with a time resolution of 1 nsec from the direction of known sources of high-energy γ-radiation.
These results demonstrate that the principle of Mini-GRAAL works, and the CESA-1 can be used as a competitive and very economical detector for very-high energy γ-rays.

1. Introduction, pro and con of the optical principle

Mini-GRAAL is a project to use the large mirror area existing in solar-heliostat arrays for the purpose of high-energy γ-ray astrophysics. For earlier reports see (Plaga, 1995; Arqueros, 1997a (technical); Arqueros et al., 1997b (Monte Carlo)). The CESA-1 heliostat array, consists of 300 heliostats, each one with 24 mirror facets of parabolical shape with a total mirror area of 39.7 m^2. The facets are aligned relative to each other ("canted") with a laser calibration system (Monterreal, 1995) so that a light source which illuminates the heliostat from the direction of its optical axis ("on axis") is optimally focused in a focal spot ata distance of about 100 m distance. The focal spots of all heliostats are located in a central tower, where the receivers measure the Čerenkov light produced by the airshowers (see figure 1). This general principle is similar to the one followed by other projects: CELESTE (E.Pare, these proceedings) and STACEE (R.Ong, these proceedings).
The optical principle for the central receiver of Mini-GRAAL is different from these projects, however. In CELESTE and STACEE the light of each heliostat is imaged onto one individual light detector via an arrangement with mirrors or lenses. This makes optimum use of each

[1]presenting author: plaga@hegra1.mppmu.mpg.de
[2]present address: IER, University of Stuttgart, Germany

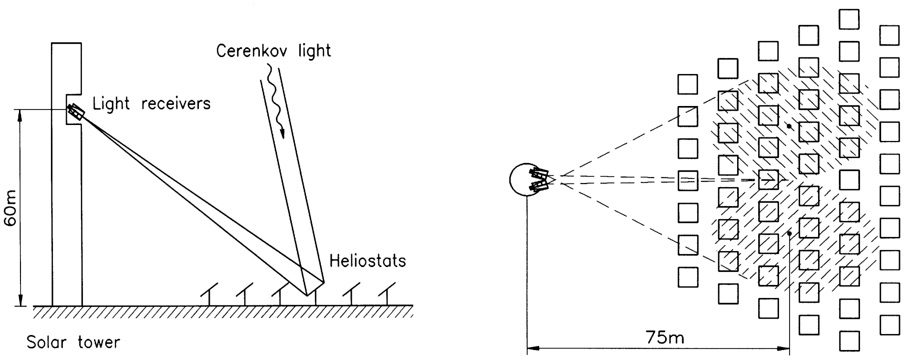

Fig. 1: left side: Scheme of Čerenkov-light concentration in experiments using heliostat fields. right side: Principle of Mini-GRAAL. 27 mirrors in two subfields are viewed by 2 cones in the central tower.

heliostat, because the signal of each heliostat is registered individually and therefore with the minimum possible night-sky background (NSB). Mini-GRAAL follows an alternative approach in which the Čerenkov light from a group of heliostats (13 to 14 in the first setup) is directed onto only one non-imaging "cone concentrator" which contains a single large-area photomultiplier tube (PMT). The light collecting cone has the form of a truncated Winston cone with an opening angle of 10^o. It is directed onto a point on the ground in the heliostat field and collects the light from all heliostats which are located within the ellipse projected by the cone opening angle on the ground (see figure 1). The main advantage of this approach is that more than an order of magnitude less individual light detectors and electronic data-registration channels are necessary, leading to a less expensive, simpler and easier to calibrate set-up. The simplicity of the setup opens the possibility of running the experiment with operators of the Plataforma Solar, without physicists being on shift the whole year. Mini-GRAAL can therefore be a cost effective instrument not only in investment but also in operating costs. The disadvantage of this approach is that the NSB, which is continuous in time, adds up for all the heliostats "viewed" by one cone. This leads to night-sky background light higher by a factor "number of heliostats viewed by one photomultiplier" than the "one heliostat - one detector" approach. This in turn leads to a higher achievable energy threshold in the detection of γ-rays. Because at energies below about 100 GeV the number of detected photoelectrons is in the Poissonian regime, the gain in threshold by the "one photomulitplier - one detector" is relatively modest, however. For the conditions at the CESA-1 field it can be shown that the minimal achievable threshold of 9 p.e. with 13 heliostats on one PMT (corresponding to singles trigger rate of about 10 MHz) could be lowered to about 6 p.e. with one PMT for each heliostat.
It should be stressed that all simulations and measurements in this report were done for an intermediate configuration with only two central Winston Cones and 27 heliostats. We have not yet simulated the performance of the final setup with four Winston cones and about 70 heliostats.

2. The site

The Plataforma Solar (2^o 21' E; 37^o 05'N) is a European research institution for solar thermal concentrating technologies operated by the Spanish "Centro de Investigaciones Energeticas Medioambientales y Tecnologicas" (CIEMAT) and the German "Deutsche Forschungsanstalt für Luft und Raumfahrt"(DLR). The climate is extremely dry (less than ten rainy days per year) and quite sunny (average of 182 clear days/year, 38 completely overcast days/year) (Wettermark, 1986). The next large city is Almeria at a distance of 40 km to the southwest; within a few km of the installation there are only a few scattered houses. A meteorological problem which leads to a loss of observation time in winter is dew formation on the relatively thin heliostat mirrors due to radiation cooling.

3. Optical performance of the heliostats in Monte Carlo and experiment

The geometrical optics of the setup were simulated by a ray-tracing code which includes mirror imperfections modeled to reproduce solar images. Figure 2 shows the results for the expected image quality of a point source. Shown is the image of a point source (a star) on the plane of the central tower in which the cones detecting the light are situated. The 1-dimensional scans lead to a σ of about 0.42 m, corresponding to an angular spread of about 0.24 ^{o}. For

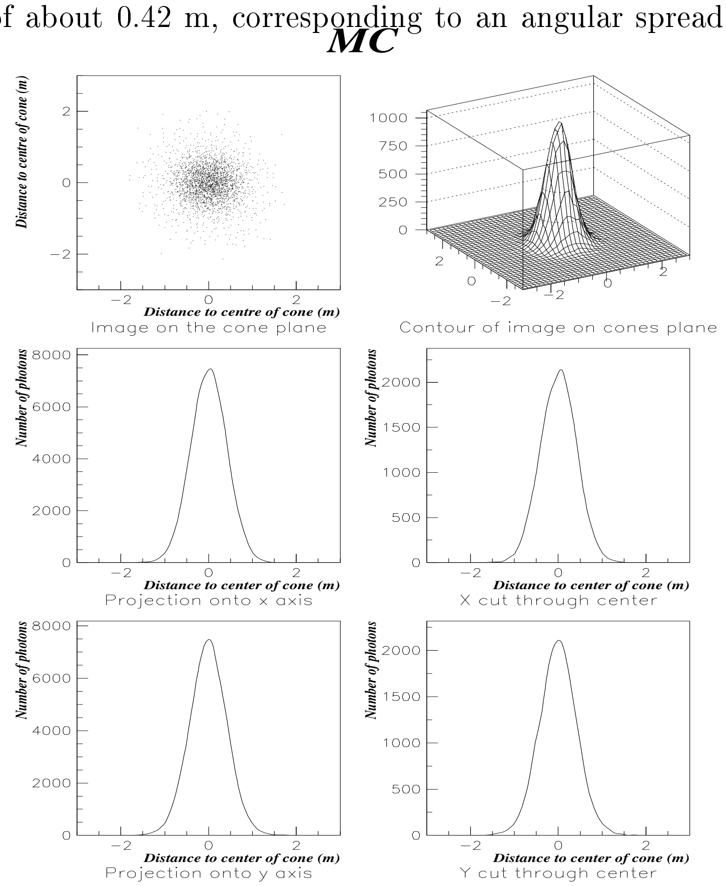

Fig. 2: Results of Monte Carlo simulations for an image of a point source on the central tower plane by 13 heliostats. The upper two images are 2 dimensional scatter and contour plots of the image, whereas the lower pictures are projections and cuts through these images in the x- and y-plane. These projections are not Gaussian because of the influence of many heliostats.

comparison figure 3 shows the measurement of a scan of a star (α Bootes) in the x (E-W) direction. This measurement was performed by measuring the DC current of the PMT in the central cone, while moving the image of the star in the E-W direction for all heliostats with the heliostat control program. The derived 1 σ-spread of the image is 0.48 m, about 14 % more than predicted in the MC simulation.

4. The Winston Cone detectors and electronics in the central tower

The shape of the light concentrators is a truncated Winston Cone with 10^o opening angle and a diameter of 1.1 m at the front.The two cones were manufactured from epoxy resin using a wooden mold and are stabilized by aluminum bars. The interior is covered with aluminized mylar foil. The total efficiency and angular acceptance of the cone was measured with blue LEDs in the pulse mode. The efficiency (0.89±0.04 for incidence on the optical axis) agrees with a MC calculation taking into account the reflectivity of mylar foil. All events were registered

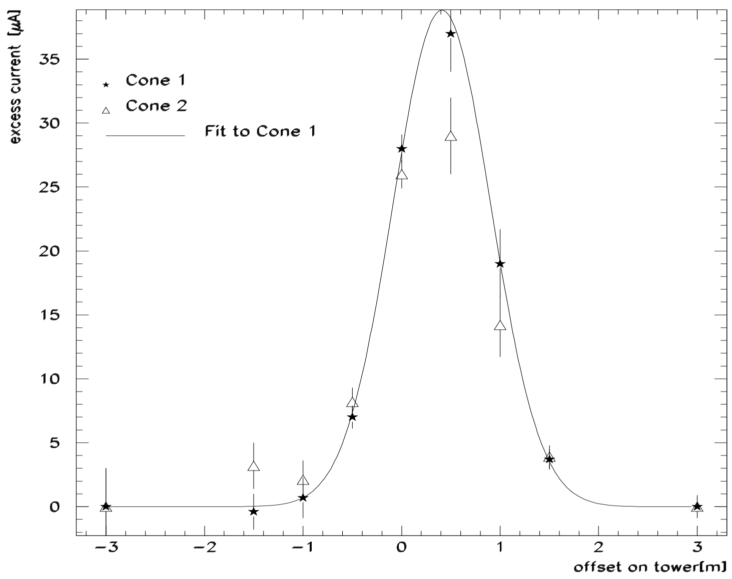

Fig. 3: Experimental scan of a star in the tower plane. Cone 1 (stars) measures 13 heliostats in the West field, Cone 2 (triangles) 14 heliostats in the East field.

with a fast (350 MHz bandwidth) 4-channel digital storage oscilloscope (Tektronix TDS 640 A), which was read out via a GPIB interface in a CAMAC crate. The events were sampled for a total time of 500 nsec (1 nsec/bin) with a pretrigger of 250 nsec for both cones individually. A selective hardware trigger was used: trains of at least three pulses above threshold with time differences corresponding to typical light-travel times were identified. This led to an event trigger rate of about 2.2 Hz under good meteorological conditions.

5. Experimental runs

There have been three measurement periods in May 1996 (for tests) and December 1996 and March 1997 (with data taking). A total of 73000 events were recorded with full waveform sampling. The weather was not ideal in the last two periods. Because of this only about 20000 events were registered under good meteorological conditions practically all during March 1997. The observation targets in March were the Crab nebula, Mkn 421, Mkn 501 and the EGRET source 4C 38.41. Figure 4 shows a typical shower as registered by both cones. Each heliostat produces a pulse with a FWHM of about 4 nsec which arrives at different times at the central receiver due to different light travel times. The expected pattern of pulses as expected from the geometry of the setup with a given source direction (shown on the right side of the figure

4) is matched with the experimental pattern, and the heliostats which produced a given signal are identified. In the next step Gaussian fits are performed on the experimental signals in $\pm$ 5 nsec windows determined from the expected pulse pattern. This allows to determine the arrival time of each pulse with a precision of about 300 psec and its amplitude with a precision of a few percent. The pulse arrival times inferred for each heliostat in this way were fitted to a

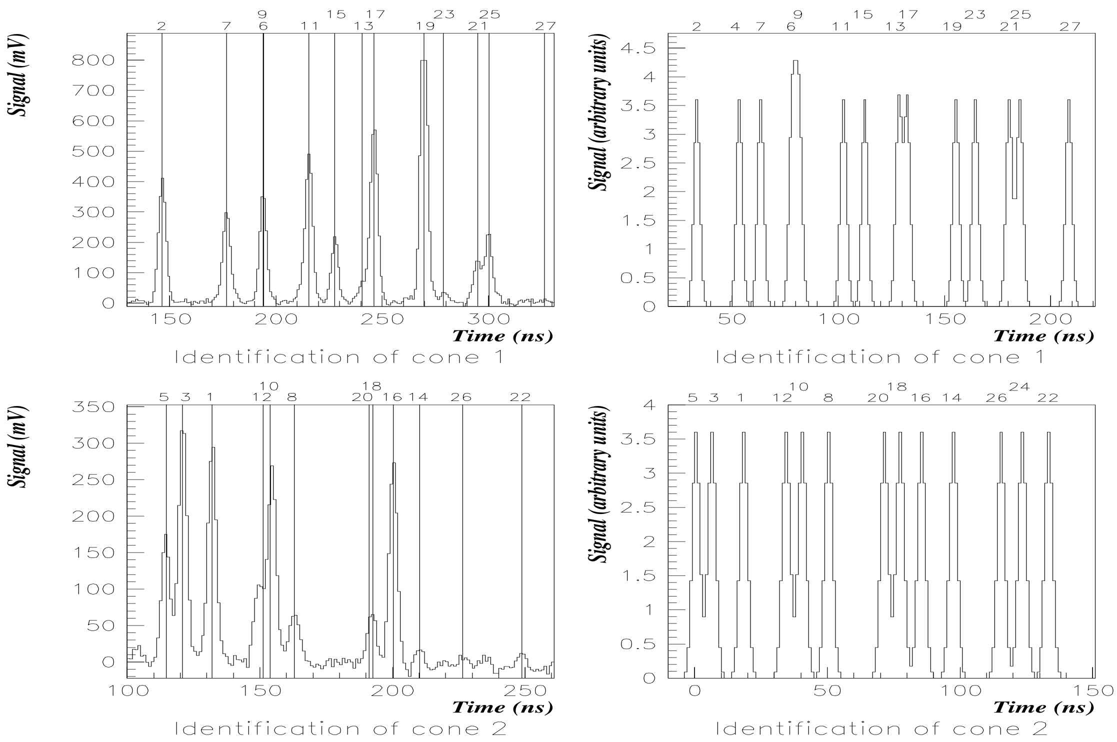

Fig. 4: Image of an experimental shower (probably a proton shower with about 2 TeV primary energy) in the two receiver cones (left side). The identified peaks are marked by vertical lines with identification numbers on top. On the right hand side the expected pulse pattern for the given source direction is plotted. In both traces all but one of the used heliostats have been identified. 1 photoelectron corresponds to 1.8 mV.

plane in order to measure the arrival direction of each shower. In case more than one peak overlapped, a multiple-peak Gauss fit was performed, and a heliostat identification based on minimizing the χ^2 was done. This analysis was carried out for both subfields individual and combined. The method was tested with MC simulations and then applied to the measured data. The reconstructed directions were found to center around the expected source direction within about 0.15 ^{o} for both Monte Carlo and experimental data. This is an independent test of the pointing of the heliostat field. The angular resolution σ_{63} with the present setup is about 0.32 ^{o}. As an example the reconstructed data of a 30 min on and off (taken consecutively in 10 minute intervals) on the March 13, 1997 are shown in figure 5. The number of events with an arrival direction reconstructed in angular intervals from the source direction is plotted. This results in a plot similar to the "α plots" of conventional imaging air-Čerenkov technique. For comparison the expected signal of γ on-source showers with a primary energy of 200 GeV are also plotted. The experimental showers extend out to about one degree which corresponds to the typical size of hadron induced showers. On and off run lead to reproducible results. *It is* *clear that Mini-GRAAL is not more dependent on performing "off" runs than other Čerenkov devices.* In principle it would be possible to perform only "on runs" in a "discovery mode" and to infer the background from the events with an angular distance of more than about 1.2 degrees. The short total observation time does not yet allow to identfy a signal in the data up to now.

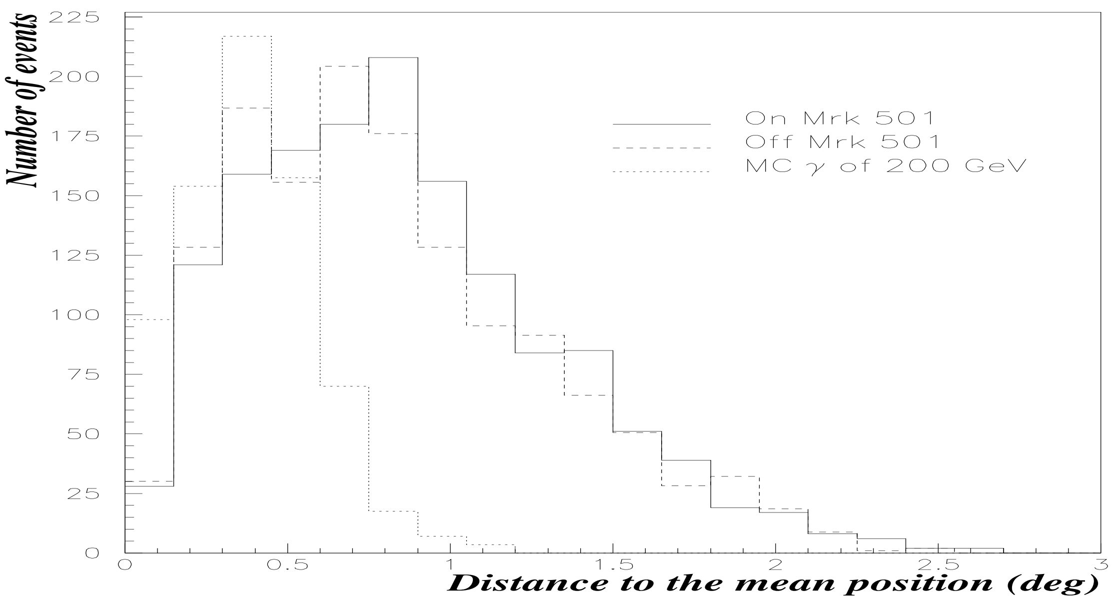

Fig. 5: On/off run results of one hour of observation under very good meteorological conditions for the source Mrk 501.

6. Gamma/hadron separation and expected performance

The γ/hadron suppression in Mini-GRAAL and similar experiments is based on the intensity distribution of the Čerenkov light which is much more irregular and spotty in hadron than in photon induced showers especially at low energies (Portocarrero, 1997). To estimate the Q-factor achievable in the present two-cone setup we tested the following rejection method with the detector Monte Carlo. The total mean square deviation of all light amplitudes from the mean was calculated for each heliostat, for MC generated hadron showers (primary energy 1 TeV) and γ showers (200 GeV). A parameter called "hadronicity" (Ong et al.,1995) was defined as the sum of these deviations over all heliostats. Figure 6 shows the distribution of the "hadronicity" values for the two primaries. If a cut on the first two or three hadronicity bins is performed a hadron suppression of a factor of about 30 and a quality factor Q of about 3 is achieved.

The energy threshold with the present 2 Cone setup was estimated to be about 190 GeV (the effective area is about 20000 m^2 at this energy). Taking into account the total trigger rate of 2.2 Hz, a hadron suppression factor of 30 and an angular resolution of 0.32 ^{o} which leads to a further suppression of background, the sensitivity for 100 h observation time of the present setup is expected to be about $3 \cdot 10^{-12}$ cm^{-2} sec^{-1}. The final four Cone setup up is expected to reach a lower threshold by about a factor of two and to improve also angular resolution and hadron suppression.

It is our aim to operate Mini-GRAAL with 4 Cones on all nights with good observation conditions on a new dedicated platform at 70 m height. The experiment is simple enough (four

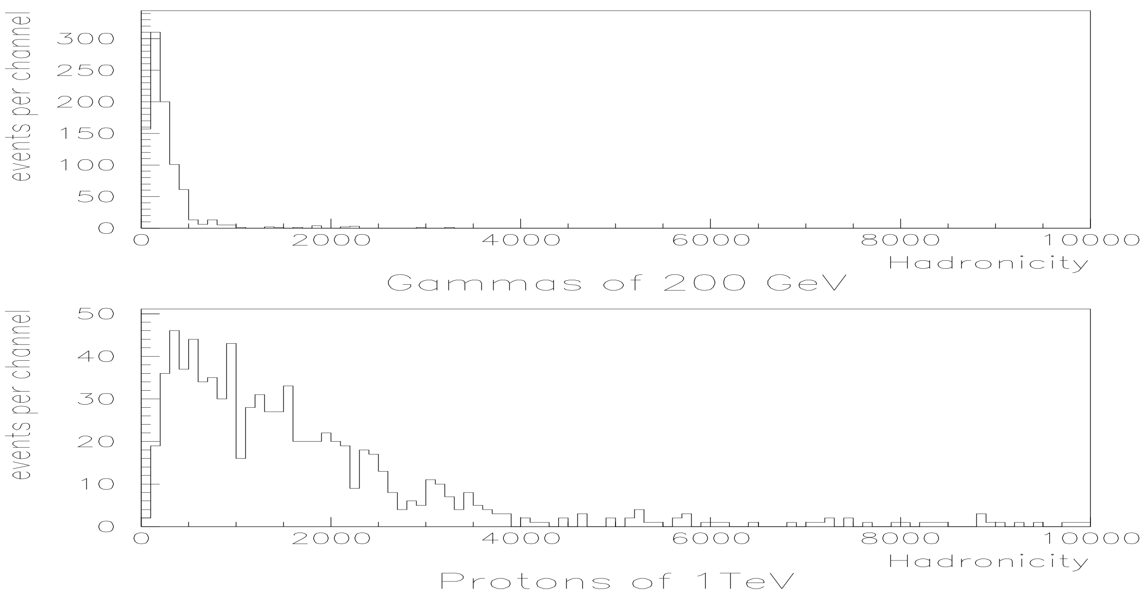

Fig. 6: Distribution of "hadronicity" values for γ and hadron induced events in a Monte Carlo simulation (detector included).

Table 1: Performance summary

	Present 2-Cone setup	Estimated for 4-Cone setup
angular resolution σ_{63}	$0.32\ ^o$	$\approx 0.2\ ^o$
energy threshold (20000 m^2 detection area)	190 GeV	$\approx$ 100 GeV
Q factor (only shower properties)	3.2	similar
5 σ flux sensitivity (100 h)	$1.5 \cdot 10^{-11}$ cm^{-2} sec^{-1}	similar

data taking channels, no moving parts in the central detector) to be operated also without specialists on site by normal operators of the PSA.

7. Acknowledgements

We thank the staff of the PSA especially A.Valverde for their enthusiastic support. We thank the DFG,DAAD, CICYT, and the Gobierno Vasco for support.

References

Arqueros, F. et al., Proc. 25th ICRC (Durban),5,149 (1997a).

Arqueros, F. et al., Proc. 25th ICRC (Durban),5,153 (1997b).

Monterreal, R.,PSA Report, R12/95 RM (1995).

Ong,R.A. et al.,Proc. Padova Workshop on TeV Gamma-Ray Astrophysics,(Padova),M.Cresti ed.,261 (1995).

Plaga, R. et al., Proc. 24th ICRC (Rome) ,1, 1005 (1995).

Portocarrero,S. and Arqueros, F., J.Phys. G (in press).

Wettermark,G., "The solar power plants at Almeria", Energy Research Commission, Stockholm 1986.