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Observation of the optical pulsation of the Crab pulsar with MAGIC and CT1: first tests

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Abstract

Due to their huge reflectors, Cherenkov telescopes are extremely sensitive to astronomical objects in the optical range. In particular the optical photon flux causes an increase in the photomultiplier DC currents. Furthermore the extremely fast response of PMs make them ideal detectors for fast (subsecond) optical transients like pulsars. An attempt has been made to detect the optical pulse of the Crab pulsar with HEGRA CT1 and further tests have been done with a PM of the future MAGIC camera to ellucidate if a detection is feasible.

Contents

1 Introduction

IACTs can be used to detect the optical emission of an astronomical object through the increase it generates in the currents of the camera pixels. Each of these pixels has typical fields-of-view in the order of 0.1-0.3°. Hence when an IACT follows a typical astronomical object, its optical emission is fully contained inside the telescope central pixel.

Since the Crab pulsar shows pulsed emission in the optical wavelengths with the same frequency as in radio and most probably of VHE γ-rays, we try to use the central pixel of CT1 and MAGIC to monitor the optical Crab pulsation. This allows to calibrate our ephemeris software when looking for VHE pulsations. Since the astronomical community does not monitor the Crab pulsar continuously in radio or optical, it may also help to serendipitiously discover pulsar glitches or period irregularities.

The optical pulsed emission of the Crab pulsar has already been detected using IACTs [Srinivisan et al., 1997] and other Cherenkov detectors [De Naurois et al., 2001]. Here we will study the feasibility of this detection using CT1, in order to apply later the same method in the MAGIC telescope.

We calculate the photoelectron rate in the central pixel, and therefore, the time needed to detect a signal, by integrating this expression:

$$Rate = \int \frac{I_o(\nu)}{h \cdot \nu} A \cdot R \cdot QE(\nu) d\lambda \tag{1}$$

where A is the collection area, R is the mirror reflectivity, QE the photo-detector quantum efficiency and $I_o(\nu)$ is the pulsar flux at the Earth.

Defining the **basic scaling parameter**[de Jager et al.,2001]:

$$x = p\sqrt(N) \tag{2}$$

which holds for any test for uniformity on a circle (after folding the arrival time with a test period). The pulsed fraction is p $=N_{pulsed}/(N_b + N_{pulsed})$, where N_{pulsed} is the number of pulsed events and N_b the number of background events. The total number of events is given by N = $(R_{pulsed} + R_b)$T, with T the observation time, R_{pulsed} the pulsed signal rate and R_b the background rate.

This parameter will give us the significance of the signal and the detection time.

The atmospheric extinction is included too. We used the data from the Calsberg Meridian Telescope (CMT) at La Palma.

2 Theoretical results

The optical spectra of the Crab pulsar main pulse and the spectrum of the underlying nebula [Carramiñana et al., 2 follow a power law:

Flux	K	α
Main pulse	5.9×10^{-15}	$+0.2 \pm 0.1$
Interpulse	1.9×10^{-15}	$+0.2 \pm 0.1$
Underlying nebula	8×10^{-12}	-0.4 ± 0.1

Table 1: *Flux in the 0.1 phase window centered on the main pulse and interpulse.*

Where, $F_\lambda = K \times (\lambda/\lambda_o)^{-\alpha-2}$, $\lambda_o = 6000$ Å, 5000 Å $< \lambda <$ 7500 Å. Fluxes are in ergs $\cdot s^{-1} \cdot$ Å^{-1}.

The useful wavelength range is 3000-8000 Å.

In our study we also took in account the influence of the light of the sky (NSB), the intensity of which has been measured at La Palma, at the site of the HEGRA experiment [Mirzoyan,R. et al.]

$$I = (1.7 \pm 0.4) \cdot 10^{12} ph \cdot m^{-2} \cdot s^{-1} \cdot sr^{-1} \tag{3}$$

with a pixel FOV of 0.25° for CT1 and 0.1° for MAGIC. The total rate from the background will be Rb = Rate (nebula) + Rate (NSB).

The NSB rate will be:

$$R_{NSB} = I \cdot A \cdot QE \cdot Reflectivity \tag{4}$$

where A is the mirror area (10 m^2 for CT1, 250 m^2 for MAGIC), QE the quantum efficiency of a PM (20 %) and the reflectivity is $\sim$ 80 %. Therefore, for the Crab pulsar we obtain:

Telescope	Main Pulsar Rate (phe $\cdot s^{-1}$)	Nebula Rate (phe $\cdot s^{-1}$)	NSB Rate (phe $\cdot s^{-1}$)	Background Rate (phe $\cdot s^{-1}$)
CT1	1.406×10^5	1.741×10^8	4.067×10^7	2.148×10^8
MAGIC	3.495×10^6	4.329×10^9	1.618×10^8	4.491×10^9

Table 2: *Currents (in photo-electrons/s) induced by the optical emission of the Crab pulsar in the central pixel of the CT1 and MAGIC telescopes.*

And a value of the basic scaling parameter of:

$$X_{ct1} = 10\sqrt{\frac{T}{1sg}} \tag{5}$$

$$X_{MAGIC} = 52\sqrt{\frac{T}{1sg}} \tag{6}$$

This calculation of the Crab pulsar rate shows that it is possible to detect the Crab optical pulse with the CT1 telescope in T=90 ms, with a significance of 3σ, and even better, with MAGIC, where the main pulse can be detected within 5 ms, which is the approximate duration of this pulse. This implies that MAGIC should have the capability of monitoring the Crab on a pulse-by-pulse basis.

3 First test in CT1

The first tests were performed in La Palma in February 2002. We tried to detect the pulsed optical signal of the Crab pulsar with CT1. The tests we did are described in this section.

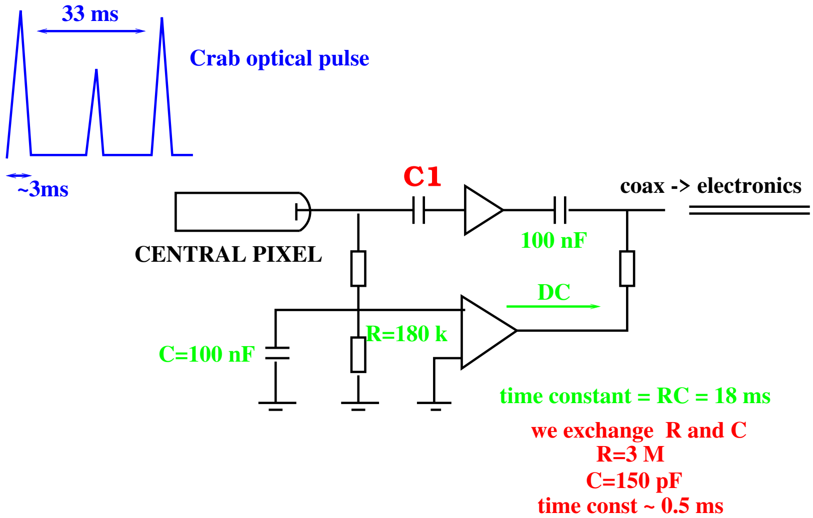

Figure 1: *Exchange in the base of the central pixel base to reduce the integration time*

The output signal of a PM in CT1 is split in two branches: a "fast branch or **AC branch**" designed to transmit the fast signals generated by the showers (in the order of some ns) and a "slow branch or **DC branch**" designed to monitor the DC current of the pixel (see figure 1). Both branches are transmitted over the same coaxial cable to the electronics room. The slow branch has a long integration time in the order of 18 ms given by a 180 KΩ resistor and a 100nF capacitor.

For the purposes of our experiment this time constant must be smaller that the typical time of the pulse variation. Taking into account that we want to detect a pulse of ~3 ms, we exchange the base for a new one with R = 2 MΩ and C = 100 pF. This corresponds to a time constant to 0.5 ms. The resistor was selected so that the output voltage in the acquisition card is around 4 V.

For the data acquisition we use a card PCI NI6034E of National Instruments (~1000 euros), with 16 analog inputs, each one with 16-bit resolution and it can get up to 200 kS/s. We operated it at 1 and 2 KS/s (2000 samples per second). The present software allows only to take 60000 samples.

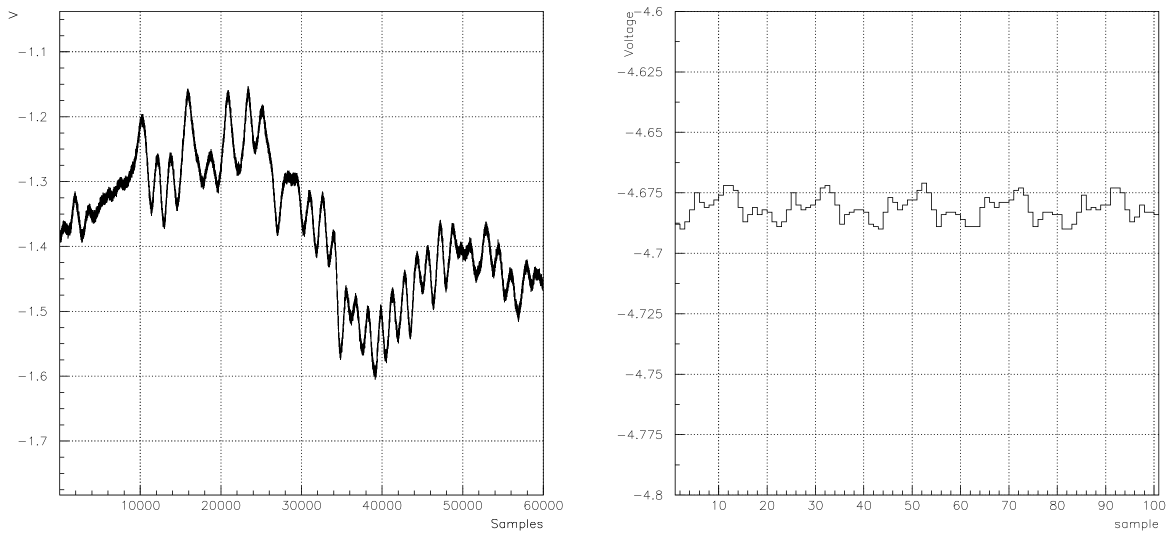

Figure 2: *Temporal variation of the current obtained for (a) ζ Tauri at linear pixel 117 and (b) Crab at the central pixel under strong gusts of wind. Each sample corresponds to (a) 0.5 ms and (b) 1 ms.*

Fig. 2 illustrates the results of some of the tests we performed. On the left is plotted the pixel current evolution in a 30 s run taken during a night with strong gusts of wind (~ 10 m/s). The pixel partly contains a bright star near to Crab (ζ Tauri). The light spot of the CT1 reflector is in the order of the pixel size (0.25°), so as the telescope oscillates, part of the image of the star goes in and out of the pixel. The time structure probably reflects the characteristic oscillation frequencies of the telescope mount. Similar tests using a similar setup to measure the pixel currents will be extremely helpful to understand the behavior of the pixel pedestals in MAGIC.

The plot on the right of figure 2 shows the signal we obtained when we pointed our telescope at Crab. A period of 50 Hz due to the electrical net is clearly visible. No period close to the pulsar period is observable.

We calculated the Fourier Power spectrum of the signal using two independent programs: one provided by Daniel Kranich and a second one written by ourselves using standard Labview libraries. No evidence for the Crab characteristic frequency (30 Hz) was found. As expected we clearly resolved the chracteristic electric network frequency at 50 Hz.

Since no indication of the Crab pulsar was found, we decided to calibrate the system. We installed a green LED inside the Madrid CCD box with the aim of flashing the telescope camera with pulses of ms length and digitize them using the card. This LED was driven by a NIM pulse generator in the "camac crate 1" labelled as "green LED".

After a few tests we realized that the fast light pulses resulted on much slower pulses in the pixel current. Fig. 3 shows the pixel current pulse registered with a fast scope at the pixel base. The fall time is in the order of 0.5 s. Out first guess was that this green LED had a very slow reaction time, that the pixel base was still not fast enough or that some element in the trasmission line was widening the signal.

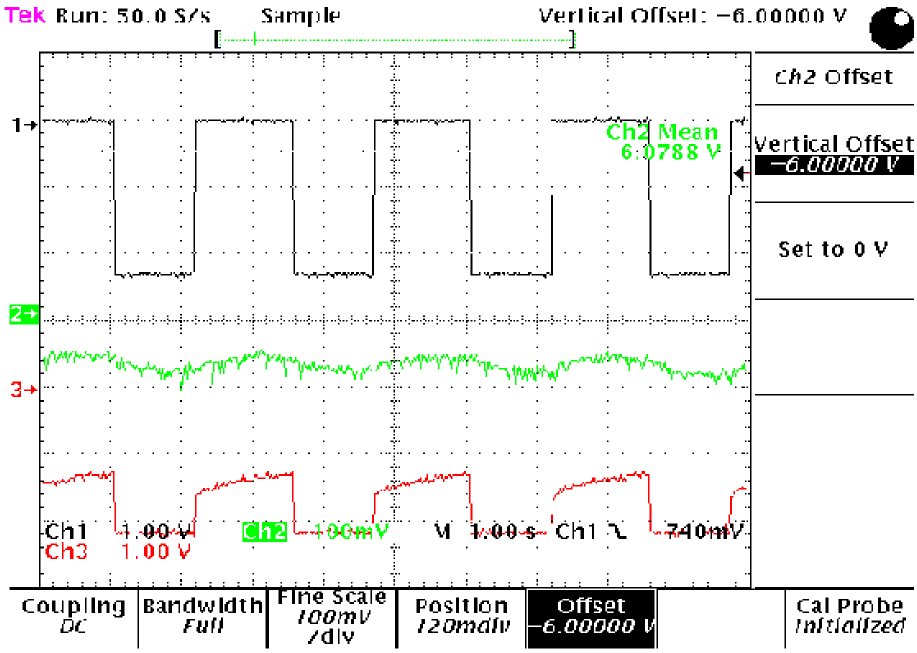

Figure 3: *Channel 1 (in black) is the voltage signal used to drive the LED (50 Ω termination). Channel 2 (in green) is connected to the base of the central pixel (1 MΩ termination) and shows rise and fall times in the order of half a second. Channel 3 (in red) is again the line going to the LED, with 1 MΩ termination.*

We also realized that the change of the resistor in the base of the PM probably results in too high a signal in the input of the DC amplifier. This amplifier is probably in saturation and outputs an erratic signal. In a second run of tests, a new base was built with a smaller resistor (500 Ω) but the same time constant <1 ms. We also replaced the slow green LED for a blue "superbright" LED. It is in addition driven at a higher voltage which is more suitable to obtain a fast light pulse. Crab was again observed during the next datataking shift, but no clear pulsed signal was detected.

4 Second test to calibrate the digitization card

Before going on with the tests on the island, we performed further tests at IFAE Barcelona, in July 2002.

Our aim was to understand the problem in February, so we tried to work out as realistic a setup as possible. We used a PM and a base undergoing the last tests before the final installation in MAGIC.

We simulated the Crab optical pulse using a fast LED.

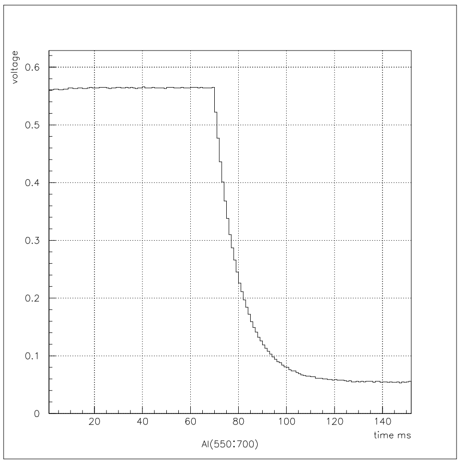

Figure 4: *Fall time measured with the digitization card using a fast LED but too slow a PM base.*

In the past months National Instruments had informed us that our digitizing card had a design error and had replaced it by a new supposedly working one. Thus our first goal was to make sure that the new card actually worked as expected. We used a pulse generator and a 1 GS/s oscilloscope. The frequency of squared pulse at the generator, the oscilloscope and the digitizing card were found to differ in less than 1%.

Again, to be able to detect the 33 ms from the Crab optical pulse simulation, we altered the PM base. In order to reduce the integration time we exchanged the original capacitator of 100 nF in the DC branch with a new one of 1 nF.

In order to simulate the Crab pulsations, we used a fast LED, (Nichia type NSPB 300 AS, of 265 nm wavelength and 4 mW output). We located the LED 7.5 m away from the PM. We estimate the luminosity given by the LED at this distance as $\sim 1 \times 10^{11}$ ph$\cdot s^{-1}$, while for the Crab pulsar we receive theoretically $\sim 2 \times 10^{7}$ ph$\cdot s^{-1}$. Therefore, we installed a filter with a reduction factor of $\sim 10^{3} - 10^{4}$ at the LED wavelength. The light pulse was attenuated to a level in the order of the NSB at La Palma, so still higher than the expected Crab pulse but in a range where we could already attempt realistic tests.

The PM DC current is taken directly from the camera mother board. The output signal was analyzed not only with the digitization card but also with an oscilloscope.

After several tests, we realized that the rise and fall times of the DC current pulses was still too slow In figure 4, the fall time is $\sim$ 20 ms. This long fall time prevents completely the detection of signals of $\sim$ 3 ms.

We checked the different elements in the setup. The pulse generator was fast enough, as well as the response of the LED. So we analyzed again the base of the PM. We removed the capacitor from the DC branch completely (that makes the DC signal noisier in all the forthcoming tests). Only then we realized that the capacitor in the AC branch (C1 in the fig. 1) also delays the signal in the DC branch. We removed it, and could finally detect the 3 ms long pulses, both at the oscilloscope and at the digitization card. Figure 5 shows the digitized signal in the card for a run of 200 samples at 1000 Hz and in the oscilloscope. Rise and fall times were measured to be shorter than 10 μs.

According to the digitizing card technical specifications it should be possible to set the input range

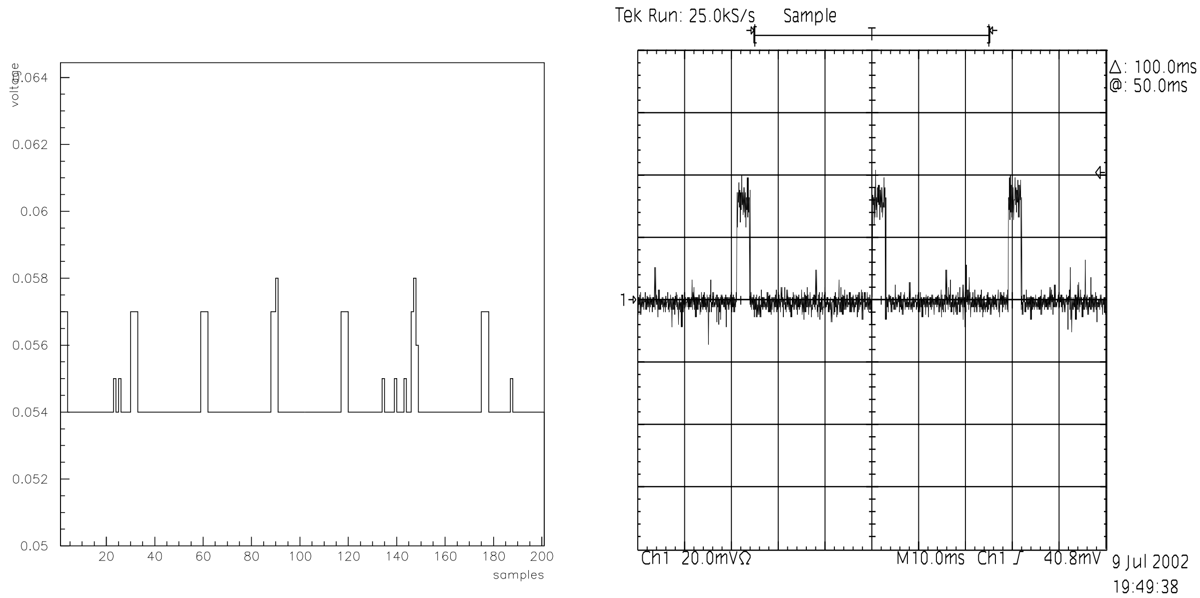

Figure 5: *Detection of the simulated Crab optical pulsed signal with the digitization card (left) and the oscilloscope (right). Each time sample in the card corresponds to 1 ms. Voltage is measured in volts.*

so that the full 16 bit dynamic range can be exploited. In our case that would mean reducing the card input range to small input voltages more comparable to our typical currents. Due to incomplete documentation in the Linux version of the driver we were however unable to use more than 10 bits for all these tests. This can be seen in the large digitizing noise of figure 5. As we shall see this limited dynamic range was anyhow enough to detect all the test pulsations which we generated. In the future we hope to be able to use the full 16 bit range.

We added another LED emitting continuous light (the standard LED in the IFAE calibration setup) The setup had been arranged so that the LED would produce light at a level comparable to the NSB at La Palma but allows some limited adjustment.

We calculated the Fourier power spectrum of the DC current signal digitized with the card. The Fourier analysis was performed using the standard Labview FFT library functions. We took runs of 20000 time samples at 1 kHz sampling rate. Crab-like light pulses were generated with and without background noise. The highest noise applied was 10 times stronger than the periodic signal and roughly corresponded to the level of the NSB expected at La Palma. Due to time limitations it was impossible to arrange a setup were the Crab-like pulses were as small as the predicted 1% of the NSB level for CT1 (see table 2). In all cases the input 30 Hz pulsation frequency is clearly visible both with and without background noise. Figure 6 shows the Fourier power spectrum for two extreme cases: no noise and a noise 10 times stronger than the pulses. Since the light pulse is very narrow the multiples of 30 Hz have also high spectral powers. This can be seen in figure 6 where the 60 Hz peak is as high as the first peak.

5 Conclusions

We conclude that the detection of the Crab optical pulsation can be performed in CT1 and MAGIC using a modified PM base with no AC branch. This is of course not compatible with normal VHE

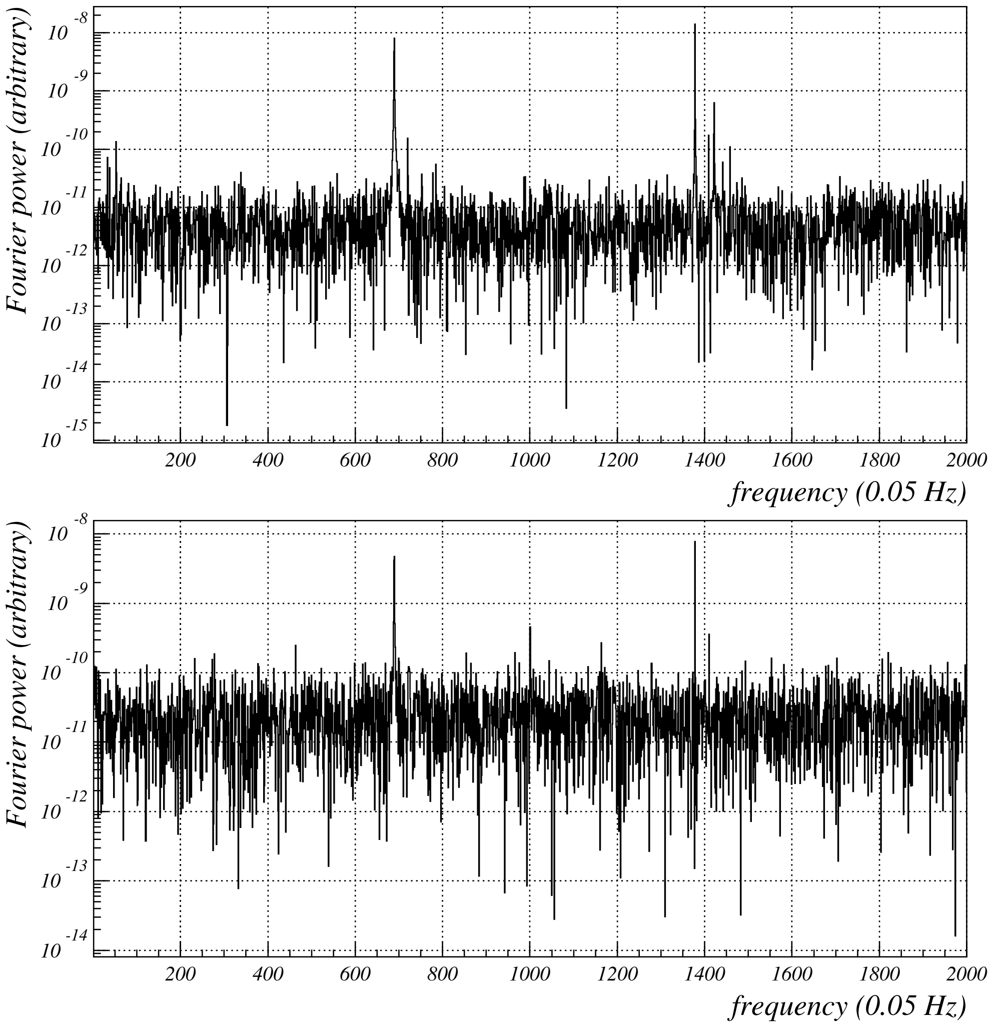

Figure 6: *Fourier power spectrum of simulated pulsations with no background noise (top), and with a background level in the order of 10 times the pulsations (bottom). The input frequency ~30 Hz and the double of this frequency display high spectral powers.*

observations and can only be considered for the central pixel of the telescope camera.

We have also considered to reduce the capacitance of C1 in the AC branch in two orders of magnitude. But this would strongly affect the Cherenkov pulses (undershoot etc).

We intend to repeat the tests with Crab at La Palma using CT1 and a special base with reduced capacitance in the DC branch and no AC branch. We would also like to equip a PM for the central pixel of MAGIC using the base manufactured at IFAE and test it with Crab at the telescope during next winter.

Since the reflector spot size in MAGIC will probably be much smaller than in CT1, it may be possible to increase our sensitivity by using a diaphragm at the entrance of the winston cone. This would be particularly fruitful if we could reduce the FOV as much as to eliminate the background caused by the nebula. To decide on the diaphragm aperture we will have to wait for experimental measurements of the spot size after final adjustment with the active mirror control system.

In the long run we could exchange the PM for an HPD to increase our light sensitivity. HPDs are also much smaller than PMs and we may install several of them in the camera space allocated for the central pixel.

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References

[de Jager et al.,2001] de Jager,O.C.,Konopelko,A.,Raubenheimer B.C and Visser,B. 2001, in Proc. International Symposium, Heidelberg 26-30 June

[Carramiñana et al., 2000] Carramiñana,A.,Cadez,A. and Zwitter,T. 2000. ApJ,542:974-977

[Mirzoyan,R. et al.] Mirzoyan,R. and Lorentz,E. Measurement of the Nigth Sky Light Background at La Palma; Internal report of the HEGRA collaboration.

[De Naurois et al., 2001] De Naurois M. et al., accepted for publication in Ap.J. and astro-ph/0107301.

[Srinivisan et al., 1997] Srinivisan R. et al., in Proc. “Towards a Major Atmospheric Cherenkov Detector V”, p. 51, ed. O.C. de Jager, 1997.