

## FACT - Long-term stability and observations during strong Moon light

M. L. KNOETIG<sup>1</sup>, A. BILAND<sup>1</sup>, T. BRETZ<sup>1</sup>, J. BUSS<sup>2</sup>, D. DORNER<sup>3</sup>, S. EINECKE<sup>2</sup>, D. EISENACHER<sup>3</sup>, D. HILDEBRAND<sup>1</sup>, T. KRÄHENBÜHL<sup>1</sup>, W. LUSTERMANN<sup>1</sup>, K. MANNHEIM<sup>3</sup>, K. MEIER<sup>3</sup>, D. NEISE<sup>2</sup>, A.-K. OVERKEMPING<sup>2</sup>, A. PARAVAC<sup>3</sup>, F. PAUSS<sup>1</sup>, W. RHODE<sup>2</sup>, M. RIBORDY<sup>4</sup>, T. STEINBRING<sup>3</sup>, F. TEMME<sup>2</sup>, J. THAELE<sup>2</sup>, P. VOGLER<sup>1</sup>, R. WALTER<sup>5</sup>, Q. WEITZEL<sup>1</sup>, M. ZÄNGLEIN<sup>3</sup> (FACT COLLABORATION)

<sup>1</sup>ETH Zurich, Switzerland – Institute for Particle Physics, Schafmattstr. 20, 8093 Zurich

<sup>2</sup>Technische Universität Dortmund, Germany – Experimental Physics 5, Otto-Hahn-Str. 4, 44221 Dortmund

<sup>3</sup>Universität Würzburg, Germany – Institute for Theoretical Physics and Astrophysics, Emil-Fischer-Str. 31, 97074 Würzburg,

<sup>4</sup>EPF Lausanne, Switzerland – Laboratory for High Energy Physics, 1015 Lausanne

<sup>5</sup>University of Geneva, Switzerland – ISDC Data Center for Astrophysics, Chemin d'Ecogia 16, 1290 Versoix

[mknoetig@phys.ethz.ch](mailto:mknoetig@phys.ethz.ch)

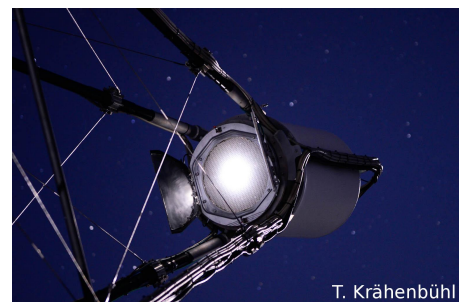
**Abstract:** The First G-APD Cherenkov Telescope (FACT) is the first Cherenkov telescope equipped with a camera made of silicon photon detectors (G-APD aka. SiPM). Since October 2011, it is regularly taking data on the Canary Island of La Palma. G-APDs are ideal detectors for Cherenkov telescopes as they are robust and stable. Furthermore, the insensitivity of G-APDs towards strong ambient light allows to conduct observations during bright Moon and twilight. This gain in observation time is essential for the long-term monitoring of bright TeV blazars. During the commissioning phase, hundreds of hours of data (including data from the the Crab Nebula) were taken in order to understand the performance and sensitivity of the instrument. The data cover a wide range of observation conditions including different weather conditions, different zenith angles and different light conditions (ranging from dark night to direct full Moon). We use a new parametrisation of the Moon light background to enhance our scheduling and to monitor the atmosphere. With the data from 1.5 years, the long-term stability and the performance of the camera during Moon light is studied and compared to that achieved with photomultiplier tubes so far.

**Keywords:** FACT, Cherenkov, telescope, G-APD, SiPM, calibration, Moon, gamma-rays, remote

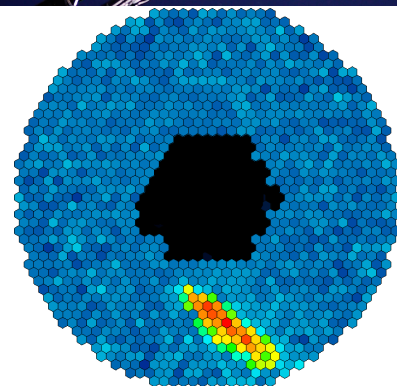
### 1 Introduction

The First G-APD Cherenkov Telescope (FACT) on the Canary Island of La Palma is the first Cherenkov telescope using novel silicon light detectors called Geiger-mode avalanche photo diodes (G-APD) or silicon photomultipliers (SiPM) instead of photomultipliers. These new detectors are compact, robust and can be used - unlike their predecessor - during strong ambient light. Since October 2011, the telescope is operated at the Observatorio del Roque de los Muchachos (ORM, 2200m a.s.l.) [1] and hundreds of hours of observations were conducted in order to understand the system. The background light conditions during data taking ranged from dark night to full Moon, and even the full Moon was once tracked in order to study response of the G-APD camera during the most extreme light conditions (Fig. 1).

FACT is, since summer 2012, also the first remotely operated Cherenkov and will eventually be the first fully robotic telescope of it's kind [2]. This is largely possible due to the stability and robustness of the novel light detectors. All of these properties benefit the main goal of FACT, which is to continuously monitor TeV Blazars over several years, in order to understand their variability and flaring behaviour. In the commissioning phase, FACT has already started to collect large datasets from selected TeV Blazars [3].



T. Krähenbühl



**Figure 1:** Top: The FACT telescope tracking the full Moon. Bottom: An event while tracking the full Moon on the 23. June 2013. For this measurement, the power for the central patches was disabled.

## 2 Strong background light - technical considerations

Today's Cherenkov telescopes are equipped with light concentrators, which prevents most of the ambient light from entering the focal plane detector. The detected night sky background in the field of view of the camera is, for a dark night in the visible band, typically  $1.7 \cdot 10^{12} \text{ph m}^{-2} \text{s}^{-1} \text{sr}^{-1}$  [4].

When the Moon rises above the horizon, the situation changes. The amount of scattered Moon light in the field of view depends on the angular distance of the observer to the Moon, the zenith positions of the source and the Moon, and with the Moon phase. Furthermore the atmospheric conditions can rapidly change the amount of scattered Moon light [5, 6]. The amount of background light can go up by about a factor 1000, when looking close to the full Moon. These considerations equally apply to the few minutes of twilight every night.

When observing with background light, one has to consider the possible damage to the light detectors. For photomultipliers this means the degradation of the last dynode [4]. In the past, observations of Cherenkov telescopes during Moon time were using UV filters [7], solar blind photomultipliers, or a lowered photomultiplier high-voltage [8], in order to reduce the amount of current coming from the scattered Moon light. Today's Cherenkov telescopes use UV filters [9] and experiment with lower high-voltage, or standard voltage settings and higher trigger thresholds [4] for Moon light and twilight observations. Around full Moon there is a gap of few days, where observations with current telescopes is not feasible [4].

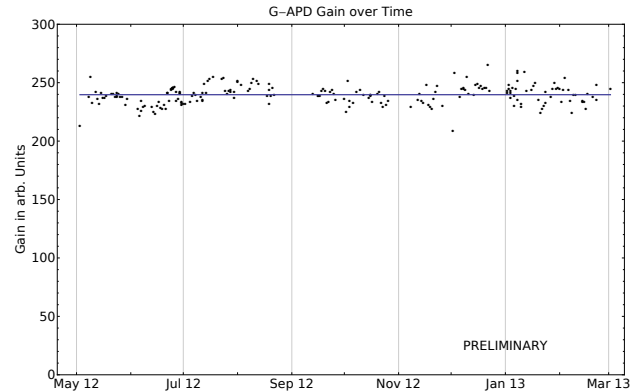
These above mentioned approaches are either time consuming, or expensive. By using G-APD as light detectors the constraint vanishes, as the G-APDs can be operated without serious degradation even during the brightest nights. Only the trigger condition has to be adjusted, depending on the changing light conditions, in order to keep the accidental trigger rate low.

On the other hand, G-APDs can saturate when illuminated, as their number of cells is limited. Therefore one has to keep in mind their dynamic range, but also the dynamic range of the digitisation and the trigger system. Lastly, when observing under strong background light conditions, the focal plane can heat up significantly because of the high DC currents. This is a challenge for the bias feedback system, which has to keep the temperature dependent overvoltage constant.

## 3 G-APD stability

A feature of G-APDs is that the breakdown voltage changes with the temperature. For this reason the FACT bias feedback initially changed the bias voltage according to the temperature coefficient specifications by the manufacturer, in order to achieve a constant gain. But also the DC current through the G-APDs has to be corrected for. From the 20. April 2012, the improved FACT bias feedback was commissioned, using also the DC current.

In order to prove the long term G-APD feedback stability, a night by night extraction of the G-APD dark count spectrum was done. This is possible, because G-APDs exhibit thermal induced breakdowns. In combination with the probability for crosstalk, this leads to a measurable signal spectrum, even when the FACT lid is closed [1], from which the individual pixel gain can be measured. The FACT



**Figure 2:** Mean G-APD gain over time. In April the improved feedback system was commissioned.

dark rate is no problem during regular data taking, as it is of the order of MHz per G-APD, which is a factor of ten less than the background rate from a dark night sky.

The results can be seen in Fig. 2. Our data from May 2012 until March 2013 indicate that the mean camera gain is stable with a standard deviation of  $\sigma_t \simeq 3.4\%$ . From a similar analysis we deduce that our gain homogeneity in the camera is  $\sigma_{pix} \simeq 4\%$ .

As shown in [6], the rate of triggered Cherenkov flashes for high enough threshold is independent of ambient light condition if the bias voltage is correctly adjusted.

The method to verify the calibration relies on dark counts and crosstalk only and is simpler, cheaper and more reliable than an external calibrated light source, as needed for photomultiplier cameras. These data show that it is possible to reliably calibrate a G-APD camera over many months using nothing but the "off the shelf" G-APD datasheet.

## 4 Prediction of the brightness of Moon light

The Moon illuminates the earth with reflected sun light. Krisciunas and Schaeffer proposed [5] a model for the calculation of the amount of photons detected, depending on the angular separation of the observer to the Moon, the zenith distance of the source and the Moon, and on the Moon phase.

Unfortunately, comparing the measured currents to this model shows large spread (Fig. 3 top). It is therefore remarkable that a simple empirical formula could be found to explain the DC currents during observations better (Fig. 3 bottom), where we define the Light Condition LC, dependent on the zenith distance of the Moon  $Z_{Moon} < 90^\circ$ , and the Moon phase expressed as the illuminated fraction  $A$  as

$$LC(Z_{Moon}, A) = \cos(Z_{Moon}) \cdot A^{2.5} \quad (1)$$

Which is proportional to the DC current in the camera. The two linear parameters of the model can be extracted from a linear regression to the data. Including the zenith angle of the observer or the angular distance to the Moon into the model does not seem to influence the results much for observations  $> 15^\circ$  away from the moon. This is in agreement with the findings of others [5, 8, 4]. It turns out that for small angular distances between Moon and observer, Mie-scattering dominates, and that for angular distances bigger

than  $\sim 30^\circ$  a relatively constant background illumination can be expected from Rayleigh scattering[5, 8].

The prediction of the brightness of Moon light has become an important ingredient, in order to successfully schedule observations. With this model and its accuracy it is now for the first time possible to detect significant deviations from the predicted current, especially when a cloud moves through the field of view.

## 5 Effect of background light on the telescope performance

The much higher ambient light drastically increases the rate of accidental triggers. Experience with FACT show that for 90% of moon, the trigger threshold has to be increased by about a factor of three [10]. How much this affects the analysis threshold is currently under investigation, using a dataset of 363h of data taken from the Crab nebula under varying conditions during winter 2012/13.

## 6 Conclusions

With a G-APD camera, the calibration light source becomes obsolete, as the G-APDs are reliably pre-calibrated. By measuring the dark spectrum they can even be used to verify their own calibration. The data show a stable calibration since the improvement of the feedback in April 2012

The FACT telescopes using G-APDs as light detectors can, as the first Cherenkov telescope, observe with strong background light up to the full Moon without any problems or modifications to the datataking routine. The FACT G-APDs have been proven to work under direct full Moon illumination, which is many orders of magnitudes brighter than the dark night sky.

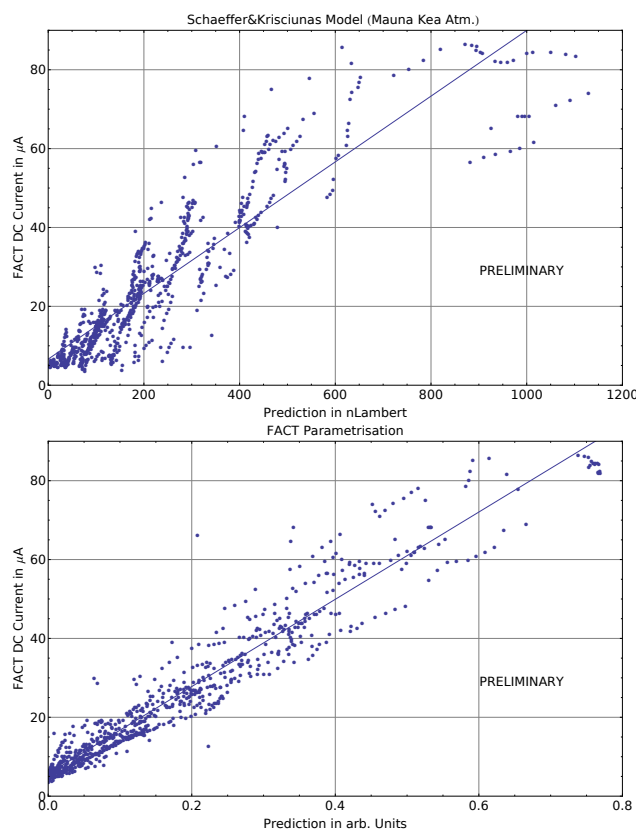
The sensitivity of the telescope is reduced by the increased trigger threshold and therefore energy threshold, which is needed to counteract accidental triggers.

In the future, we are planning to apply correction factors, obtained from the Crab Nebula, in order to determine the flux of  $\gamma$ -rays for any source zenith distance and any light condition, in addition to Monte Carlo verifications.

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**Figure 3:** Moon light prediction models. Top: the model by Krisciunas and Schaeffer[5]. Bottom: simple empirical model. Only good weather datapoints included.

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