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Small size air-Cherenkov telescopes for ground detection arrays - a possible future extension?

Merlin Schaufel[a], **Thomas Bretz**[∗a], **Johannes Schumacher**[a], **Jan Auffenberg**[a], **Maria Magdalena Gonzàlez**[b], **Ruben Alfaro**[b], **for the HAWC Collaboration**

[a] *RWTH Aachen University, Aachen, Germany*

[b] *Instituto de Fìsica, Universidad Nacional Autònoma de Mèxico, Mexico D.F., Mexico*

E-mail: schaufel@physik.rwth-aachen.de

The combined use of air-Cherenkov telescopes with ground based particle detectors is investigated. While a hybrid detection technique using fluorescence telescopes and ground arrays has been successfully applied by the Pierre Auger Observatory, this study focuses on the combination of air-Cherenkov telescopes and ground arrays for detection of TeV gamma-rays. After the successful measurement of air showers with the 7-pixel prototype telescope, an upgraded version (FAMOUS) of a combined fluorescence and air-Cherenkov telescope is now operational. It employs a 55 cm aperture Fresnel-lens in a sealed tube and a 61-pixel camera with semiconductor photo sensors (SiPM). For joint measurements, it will be synchronized with the High Altitude water-Cherenkov gamma-ray observatory HAWC (Sierra Negra, Mexico) to evaluate its prospects as an enhancement of ground based detectors. A main focus is the improvement of the energy resolution by accessing complementary shower informations with both technologies. The direct measurement of the air shower particles by the HAWC observatory also allows the characterization of the air-Cherenkov telescope, such as collection area, without any Monte Carlo simulation. Preliminary results from this study will be presented and the future potential of air-Cherenkov telescopes as an extension for ground based arrays will be discussed.

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∗Speaker.

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1. Introduction

The ground based detection of high energy gamma-rays opened a new window to the most energetic sources of radiation in our universe. Since 1989 more than 190 sources were discovered [1], which makes this topic to one of the most vivid fields in astroparticle research. With the development of imaging air-Cherenkov telescopes (IACTs), a possibility arose to evaluate sources with high resolution in spatial as well as in spectral dimension. The disadvantage of a limited duty cycle due to the restriction of nighttime observations are solved by particle sampling ground detectors for the cost of decreased angular and energy resolution. As IACTs offer sensitive and pointed observations, while ground array detectors features a wide field of view and a huge duty cycle, the detector capabilities are complementary. This study focuses on the direct combination of both technologies to enable synchronous hybrid measurements with several potential advantages. Due to shower-to-shower fluctuations, the energy reconstruction of ground detectors is limited as the number of particles reaching the ground has large fluctuations. In contrast, IACTs reconstruct the primary energy by measuring the integrated number of photons reaching the ground from different heights and therefore are less affected by these fluctuations. Using the additional energy information not only allows increased detector resolution while the IACT is in operation, it also offers the opportunity to cross calibrate the ground detector with a set of real showers. An additional benefit is the possibility to characterize the collection area and efficiency of the IACT without any simulations by using the array shower geometrical information.

In the following article, we present the plan for a proof-of-concept of a hybrid measurement using the compact wide field of view IACT FAMOUS at the High-Altitude Water Cherenkov Gamma-Ray Observatory HAWC. A small overview over the technology is given as well as information about the implemented synchronization system. A first Monte Carlo estimation of the combined energy resolution is presented. The results will be validated at upcoming field tests at the HAWC site.

2. The wide field-of-view air Cherenkov telescope FAMOUS as proof-of-concept extension for HAWC and future detectors

The High-Altitude Water Cherenkov Gamma-Ray Observatory HAWC, located at Sierra Negra (Mexico) is currently the largest particle sampling detector for ground based gamma-ray observations. The observatory consists of 300 Water Cherenkov Detectors (WCD), each with a diameter of 7.3 m and a height of 4.5 m. Each WCD is equipped with four photomultiplier tubes (PMT), measuring the Cherenkov light produced in 200,000 liters of purified water. With a footprint of roughly 22,000 m^2, a field-of-view of 2 sr and a duty cycle of more than 95 %, it is ideal for monitoring and the detection of transient gamma-ray sources [2].

After the successful start of data taking with the full HAWC detector configuration on the 20th of March 2015, different improvements are planned to further increase the detector performance. Examples include the outrigger tanks, which will help to reconstruct the core position for gamma-ray showers with an energy above 10 TeV [3]. Considering the upcoming plans for a new generation southern gamma-ray observatory this is a convenient time to put new technology to the test.

2.1 The baseline design and DAQ of FAMOUS

The imaging air Cherenkov and fluorescence telescope FAMOUS (Figure 1) is a compact refractive telescope design using a 61 pixel silicon photomultiplier camera . The optical system is built up on a sealed carbon lens barrel, hosting a Fresnel lens with an aperture of 549.7 mm and a focal length of 502.1 mm. The camera is composed of 61 pixels and three additional monitoring pixels. Each pixel is made of an aluminum Winston cone light concentrator and four silicon photomultiplier (SiPM). The used SiPMs are of the type Hamamatsu S10985-100C which are composed of an array of four Hamamatsu S10362-33-100C SiPMs [4]. It is possible to install an additional UV bandpass filter to attenuate ambient light.

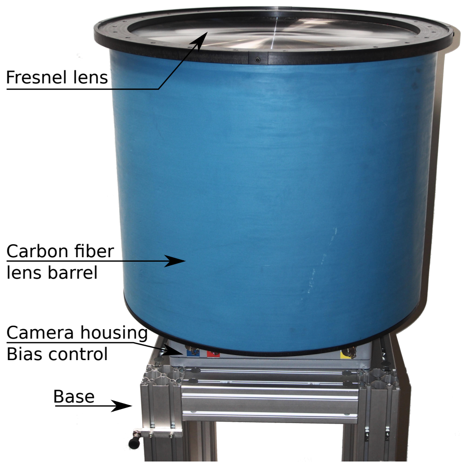


Figure 1: Compact air-Cherenkov and fluorescence telescope FAMOUS. Here equipped with a new lightweight carbon lens barrel, the UV transparent plastic Fresnel lens and the 61 pixel camera including an integrated bias control [5].

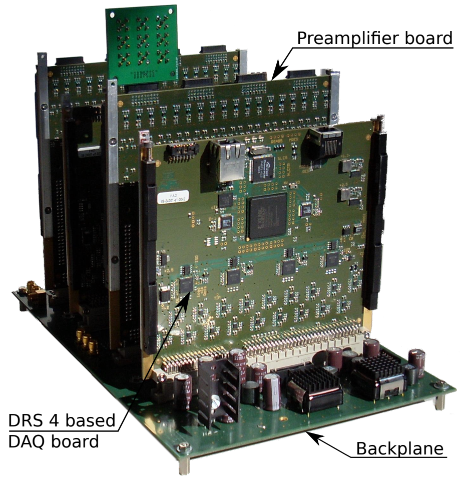


Figure 2: The FAMOUS data acquisition system using two FACT preamplifiers, trigger units and digitizer boards on a custom build backplane. The system features 72 channels, a 9-fold sum-trigger and a 2 GS/s DRS4 based digitizer [6].

The data acquisition system is based on spare parts from the FACT project [6]. Figure 2 shows the assembled boards on a custom build backplane. In detail, the system contains a SiPM preamplifier, a trigger unit and a DRS4 based digitizer [7]. The preamplifier amplifies the SiPM signals and forms an analog sum for a trigger patch of 9 pixels. This sum is discriminated and a trigger is sent to the trigger unit. The trigger unit is used to enable or disable channels in the trigger, to set the thresholds and to count and distribute the triggers. If a trigger occurs the digitizer samples the trace with 2 GS/s using DRS4 domino ring sampling chips. The whole DAQ system offers 72 channels. Besides the proven performance, another advantage of using the FACT hardware is the existing mature software framework with slight modification for the FAMOUS setup [6]. An important factor for future extension potentials is the low price of a FAMOUS like telescope of less than 10000 Euro [8].

PoS(ICRC2017)786

3. Development and test of an external detector synchronization for the HAWC Gamma-Ray Observatory

To synchronize the autonomously triggering FAMOUS telescope reliably to the HAWC data stream, a link between both systems has to be established. As the HAWC observatory is located at an elevation of 4100 m, the area is highly exposed to lightning strikes. Therefore, a non-conductive solution is important to protect the HAWC DAQ from high transients. For this purpose, a low-cost single channel TTL-Optical transceiver for multi-mode fibers was developed. With this device, it is possible to safely connect every system in the ambit of the HAWC area with the main DAQ (see Figure 3).

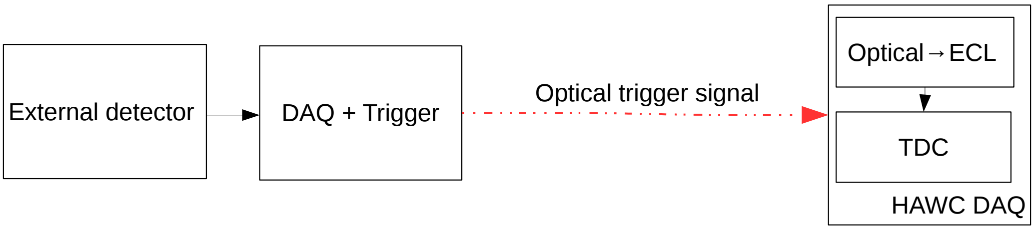


Figure 3: Diagram of the fiber trigger system. A trigger generated from an external detector with own DAQ and trigger system is converted to an optical signal. Inside the HAWC main DAQ housing it is back-converted to ECL, fed into the TDC and stored in the HAWC data-stream as additional external hit flag.

To ensure synchronization with the HAWC detector, a calibration of all signal delays is necessary. To test this calibration a coincident measurement with a single WCD was carried out. A $30 \cdot 30\,\mathrm{cm}^2$ plastic scintillator panel, equipped with a SiPM as sensing element, was placed centered on top of a central WCD tank. As readout system, a 100 MS/s 14 bit FADC and a FPGA based trigger system from a commercial *Analog Discovery 2* was used [9]. The trigger signal was connected to the HAWC time-to-digital converter (TDC) using the TTL-Optical transceiver. The signal from the PMT located directly under the scintillator panel was discriminated to evaluate the delay to the signal from the external detector (Figure 4). As the measured mean time-difference is compatible with the reported cable delays, it is possible to adjust the timing accordingly to the specific fiber length without repeating this experiment. As a result, it is possible to introduce external signals into the HAWC data stream. Different possible future experiments like coincident lightning detection will benefit from this system.

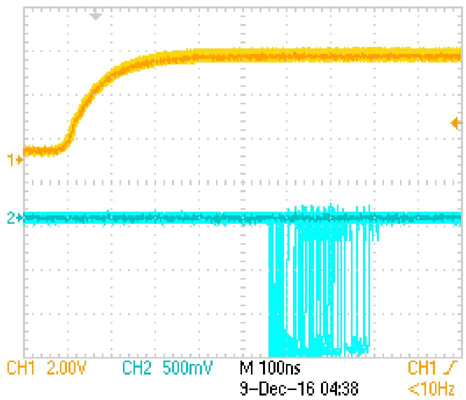


Figure 4: Measurement of the propagation delay difference of a discriminated WCD PMT signal (blue, NIM) and the scintillation detector signal (yellow, TTL), located centered over the WCD. From the mean time difference the optimal additional delay is determined.

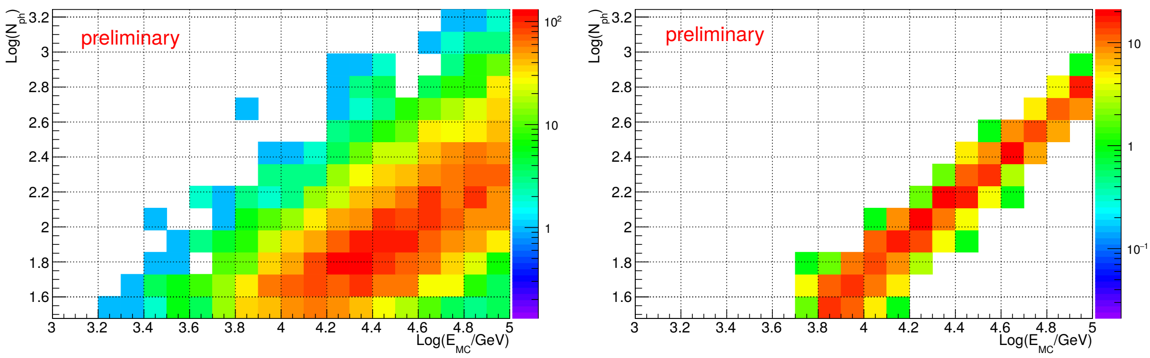
4. First simulations: A performance estimate for a combined system

To evaluate the improvements from a hybrid detection system, a joint simulation was performed. A dataset of gamma and proton induced showers were generated with the CORSIKA simulation package [10]. All photons reaching the telescope aperture at the observation level of 4100 m were propagated through the telescope using an optical parameterization which includes the transmission efficiency and refractive property of the Fresnel lens, the Winston cones, the UG11 UV pass filters and the SiPMs [11]. The outcome is a timestamp and a pixel number for every photon that was detected by a SiPM in this specific shower event. In the final measurement, the same shower would also be detected by HAWC. Therefore, all particles reaching the observation level are saved to allow a joint simulation by feeding the same events to the HAWC GEANT4 model in the future.

Table 1: Simulation parameters for the first set of gamma showers produced with CORSIKA:

Primary particle	Gamma	Observation height	4,100 m
Number of showers	30,000	Magnetic field	27.72 μT (X), 29.91 μT (Z)
Energy range	1 TeV – 100 TeV	Atmospheric model	US Standard
Shower core distance	0 m – 100 m	Shower inclination	0° – 8°

To estimate the performance for the field test, the additional information from HAWC is mimicked using smeared simulation parameters. Important parameters for the energy reconstruction are the core position (HAWC uncertainty ≈ 2 m for larger showers) and the inclination angle (HAWC uncertainty $< 0.5°$ for $E > 1$ TeV and $< 0.25°$ for $E > 10$ TeV) [2, 12]. Table 1 gives an overview over the parameters used for this simulation. In total 30,000 gamma showers were produced (test batch) and analyzed. More showers are in production.



(a) (b)

Figure 5: Correlation between primary Monte Carlo energy and number of detected photons for gamma-ray showers. (a) For a shower core distance up to 100 m to the telescope. (b) For a shower core distance of 40 m to 50 m and only showers which are fully contained in the field of view of FAMOUS. The width is clearly reduced by these simple cuts.

After applying the GEANT4 model parameterization, we exclude showers having less than 30 detected photons in a patch of 9 pixels (data acquisition design constraint). In the absence of a complete electronic simulation, this is a reasonable estimation for the trigger threshold considering the field-of-view of the telescope and the anticipated night sky background. Figure 5a shows the relation between the true primary energy and the number of detected photons for all showers that passed the threshold condition. Cutting on the shower core distance and requiring less than 30 detected photons in the outer pixel ring (full containment in the field-of-view) significantly reduces the width of the distribution (see Figure 5b).
Figure 6 shows the estimated energy resolution of a hybrid system using only the shower size (number of detected Cherenkov photons) and the shower core position. The energy is reconstructed fitting a linear model to N_{ph} (Number of photons) and E_{MC} (Monte Carlo energy) for different, but known, shower core distances. The achieved resolution improves the current resolution by a factor of two in the energy range of 8 TeV to 20 TeV. For the energy range above 20 TeV, no HAWC data is available [13]. The first results from this simulation demonstrate a significant improvement in energy reconstruction, even with a small-sized telescope like FAMOUS. With factor two better energy resolution the sampled data could serve as a Monte Carlo independent cross calibration to permanently improve the energy reconstruction of HAWC. In a next step electronic responses and the night sky background will be included in the simulation, which have little effect on the energy resolution. A more sophisticated analysis including the simulated HAWC observables will reveal whether background suppression or angular resolution can also profit significantly from the additional telescope information.

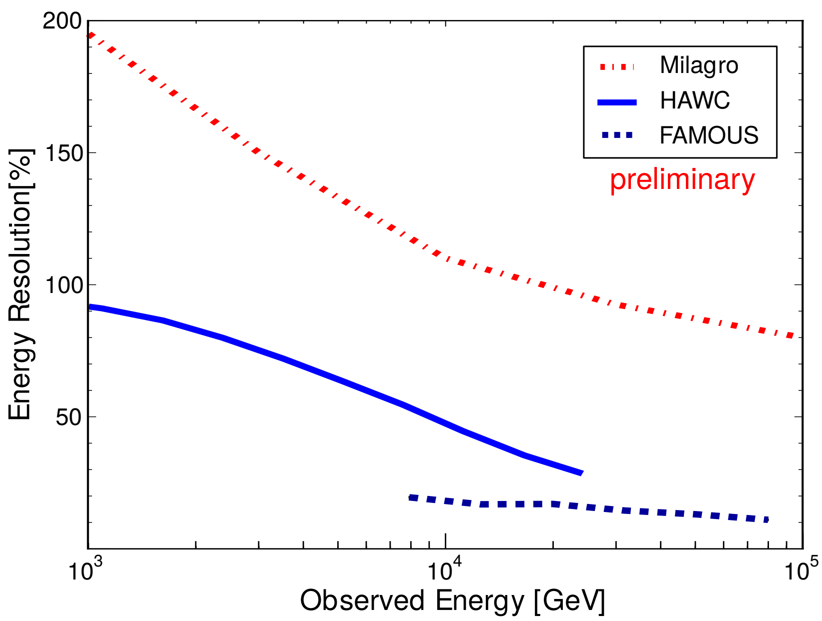


Figure 6: Energy resolution for gamma-ray showers measured with Milagro (red, dashed), with HAWC (blue, solid) [13] and with a combined system (blue, dashed). Estimation for events in the field-of-view of FAMOUS with a shower core distance of 30 m to 100 m.

5. Summary and Outlook

We presented the work to setup the compact imaging air-Cherenkov telescope FAMOUS at the HAWC site to improve its energy resolution and to test the technology for future detector setups. The implemented fiber trigger system allows to safely synchronize events from external devices to the HAWC data-stream. The use of this setup is not limited to the project as every instrument which has a logic output can be connected easily. The test and calibration of the fiber trigger timing was achieved using a scintillator panel in coincidence with a water Cherenkov detector tank. A first simulation study showed promising benefits by using not only an additional detection technique but combining both systems. The energy resolution is decreased by a factor of two only using the intrinsically good energy resolution of imaging air-Cherenkov telescopes and the additional information about the shower core distance from HAWC.

The simulation is currently improved as it misses a full electronic simulation and noise treatment at this moment. Also a joint simulation with the HAWC GEANT4 model is in development. The telescope itself is currently undergoing a rapid development including an upgrade of the Winston cone light concentrators and the usage of state of the art silicon photomultipliers. This next generation will feature improved light sensitivity and reduced energy threshold. For a possible upgrade, the optics could be enlarged to reduce the energy threshold even further and increase the overlap with the energy range of HAWC or other experiments. The FAMOUS telescope is currently being prepared for the temporary deployment and data taking at the HAWC site. A recorded shower image of a field-test in Aachen (Germany) is shown in Figure 7. A field-test at the HAWC site of several days of data taking is scheduled for July 2017.

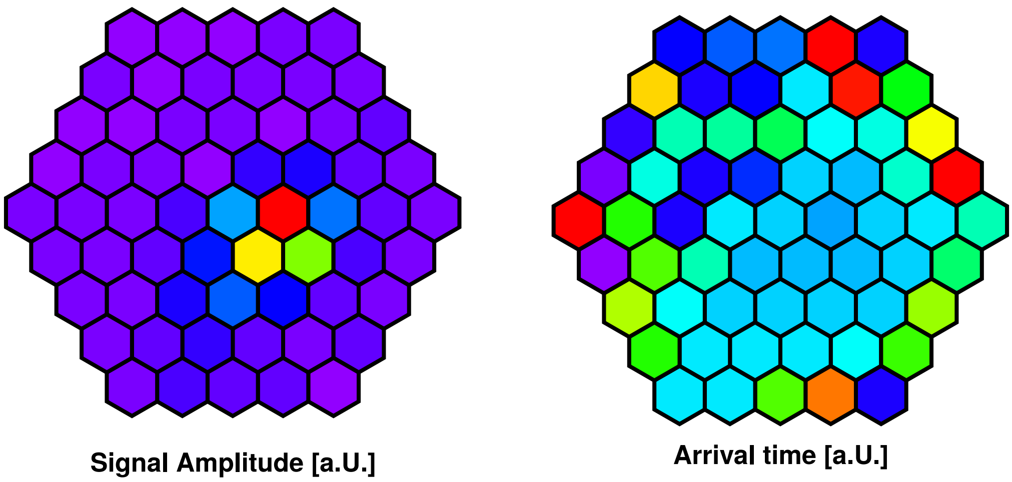


Figure 7: Potential air shower event recorded with the FAMOUS telescope in lighted urban area (Aachen, Germany) during a field-test in June 2017. Amplitude (Left plot, red: Higher light signal) and arrival time (Right plot, red: Later arrival). The shower candidate is clearly coincident, pixel without signal have random arrival times.

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