AMIGO* Proposal

Use of ANTARES optical modules in a high-altitude water Cherenkov observatory

From the bottom of the sea to the top of the mountain

* **A**ntares **M**odules **I**n a **G**amma-ray **O**bservatory

Abstract

After the success of the HAWC high-energy gamma-ray observatory, an extension of the "high altitude water Cherenkov" technique to the Southern Hemisphere is currently being discussed. The following document provides an introduction to the scientific interest and aim of this project. We discuss several proposed detector designs and illustrate preparatory work.

In this context, we put forward the AMIGO proposal: the use of the optical modules of the ANTARES high-energy neutrino telescope in this next generation water Cherenkov gamma-ray observatory.

Version: Tuesday 11th October, 2016 10:05

Expression of interest

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Disclaimer: The above list denotes colleagues that expressed their personal interest as physicists in seeing the ANTARES modules re-used in a high-altitude gamma-ray observatory. It does not imply any commitment to form a new collaboration or actively contribute to an experiment.

1 Introduction

1.1 The HAWC observatory

Building on the success of the MILAGRO [1] observatory and the VAMOS engineering array [2], the construction of the *High-Altitude Water Cherenkov Observatory* (HAWC) has been finalized in early 2015. The observatory is located near the mountains Pico de Orizaba and Sierra Negra at an altitude of 4150 m and consists of 300 water Cherenkov detectors (WCDs, cf. Fig. 1a), each holding $200\,\mathrm{m}^3$ of water monitored by four 8-inch hemispherical photomultiplier tubes. The detector covers an area of $20,000\,\mathrm{m}^2$ and deployment of the full detector took about 2.5 years (cf. Fig. 1b). During deployment, data taking with subsets of the full array allowed to verify the DAQ, prepare the reconstruction and analysis software and produce first physics results [3].

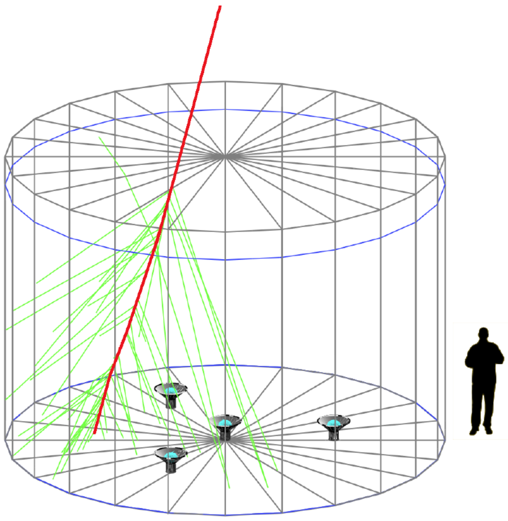
The detector records the passage of the particles in extensive air showers which have been induced by cosmic rays and gamma-rays in the atmosphere above the array. The altitude and detector size make HAWC sensitive to air showers induced by primary particles with energies between about 100 GeV and 100 TeV. Due to the different development of hadronic and gamma-ray induced showers, the two components can be separated efficiently above a few hundred GeV. The angle of incidence of the primary particle and the location of the air shower core can be reconstructed from the timing of the individual PMTs with a resolution of better than 0.1° above 10 TeV ($< 0.35^\circ$ for $E > 1$ TeV). The total charge (recorded via a pair of time-over-threshold measurements for each PMT) and hit multiplicities provide access to the primary energy with a resolution of better than 50 % above 10 TeV ($<$ 100 % for $E > 1$ TeV) [2]. HAWC monitors the high energy sky with an instantaneous aperture that covers more than 15 % of the sky. With this large field of view, the detector is exposed to 2/3 of the sky during a 24-hour period. The effective data taking duty cycle is greater than 95 % [7].

1.2 HAWC: Main science objectives

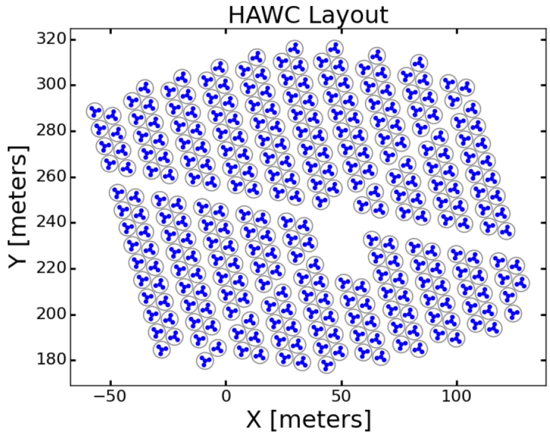
A recent detailed description of the physics potential of HAWC can for example be found in the contributions to the 34th ICRC (The Hague, 2015) [3]. In summary, HAWC is providing very-high-energy gamma-ray data with high resolution and sensitivity and hence enable detailed studies of TeV gamma-ray sources (cf. Fig. 2). The large FoV, which allows for unbiased surveys of large regions of the sky, provides enormous discovery potential of previously undetected high energy gamma-ray emission regions. Reaching similar angular resolution, the sensitivity of HAWC surpasses that of current imaging Cherenkov arrays like HESS and VERITAS around 5 TeV [4]. Its main sciences goals comprise:

- Extended gamma-ray sources are prime candidates for the wide field of view of HAWC. Interesting studies include for example the high energy extension of the Fermi bubbles [5], the Cygnus region with its cocoon of freshly accelerated cosmic rays [6] or studies of the diffuse Galactic emission.

- The large sky coverage combined with the high duty cycle enables detection and monitoring of transient sources (AGN flares, binaries, etc.). The observatory is therefore perfectly suited to provide triggers for multi-wavelength observations, a capability already successfully demonstrated by various alerts exchanged publicly and within the



(a) HAWC: tank



(b) HAWC: array layout

Figure 1: Schematic view of a single HAWC WCD (left) and the layout of the completed HAWC array (right). From [13]

VHE gamma-ray community, allowing for deep follow-up observations with Imaging Air Cherenkov Telescope (IACTs) instruments like Veritas, H.E.S.S. and MAGIC. It may even be that the energy threshold is low enough to allow for GRB observations with detailed light-curves and un-triggered detections complementing and/or replacing current instruments like Fermi-LAT.
It also permits to collect an unbiased, only flux limited, sample of gamma-ray sources which enable for example studies of the extragalactic background light (EBL), searches for dark matter, etc. An example for the longterm monitoring capabilities demonstrated by HAWC is shown in Fig. 3.

- The gamma-ray sky is currently known only up to energies of a few TeV. The high-energy domain, closely connected to the accelerators of cosmic rays beyond the knee, is currently largely-uncharted territory. The unprecedented sensitivity of HAWC to gamma-rays around 100 TeV will enable a deeper understanding of the high-energy universe but may also allow for new and exciting discoveries. A first example is the discovery gamma ray emission from the Crab extending beyond 100 TeV and the discovery of about 10 previously unknown TeV gamma-ray sources [7].

- Cosmic ray studies include the measurements of anisotropies at different angular scales and as function of energy (e.g. as Northern Hemisphere counterpart of IceCube/IceTop [8] with substantial improvements over results from Milagro [9] and other observatories like Tibet-ASγ and Argo-YBJ [10]), as well as measurements of the cosmic ray energy spectrum and possibly the mass composition.

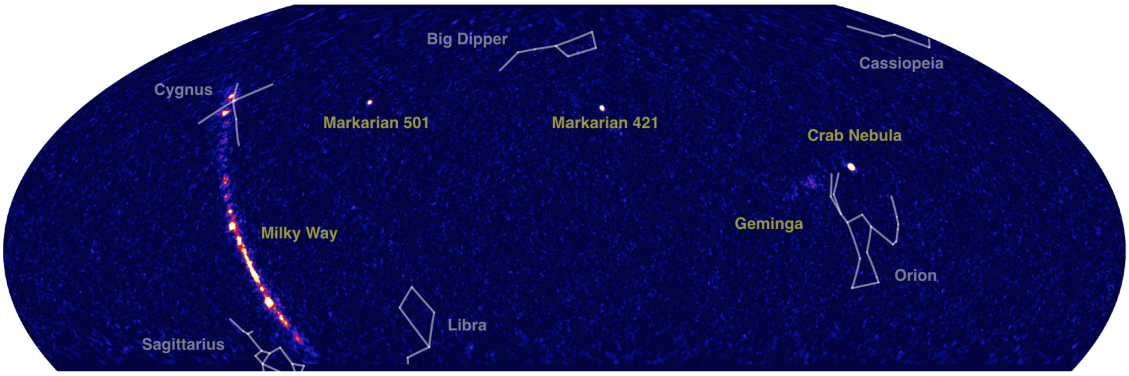


Figure 2: The high-energy gamma-ray sky seen by the HAWC observatory after its first year of data taking. From [11]

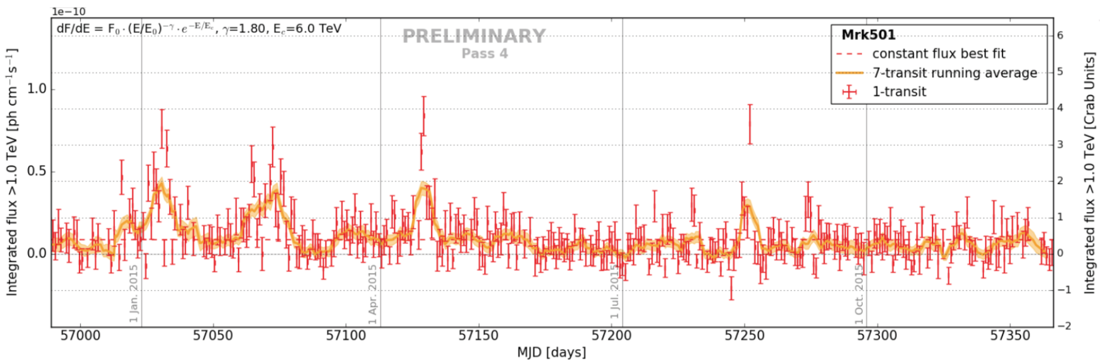


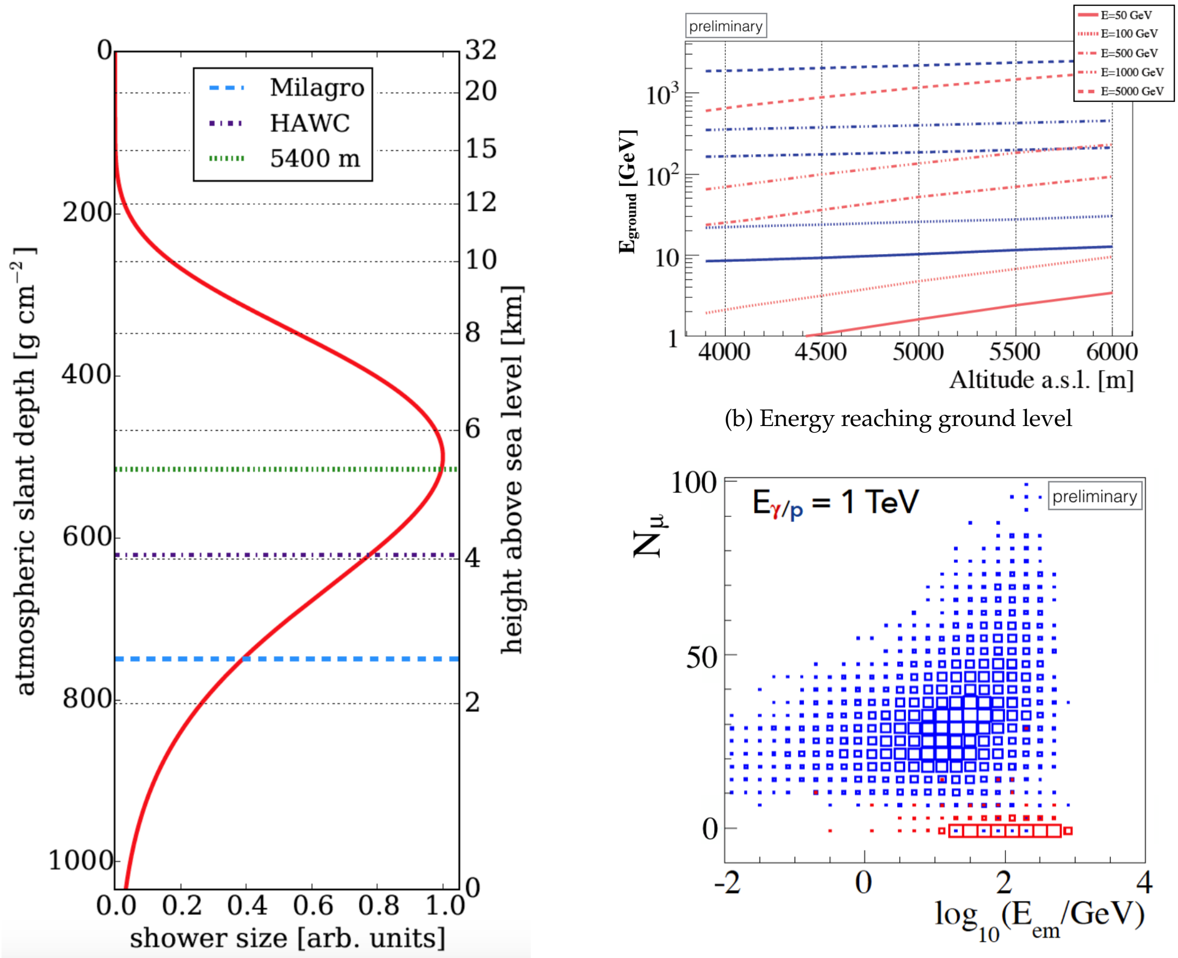
Figure 3: Long-term lightcurve of Mrk501 in VHE gamma-rays observed with HAWC. From [12]

2 A high-altitude water Cherenkov detector in the Southern Hemisphere

We here outline a few thoughts that lead us to propose a next generation water Cherenkov detector in the Southern Hemisphere.

2.1 General considerations

The sensitivity of large area water Cherenkov detector for VHE gamma-ray observations is defined by several main parameters: the location and altitude of the site, the detector area and its sensitivity to air shower particles and its capability to discriminate between hadron and gamma-ray induced air showers. All of these points are coupled to each other, for example, a higher altitude inherently results in more particles reaching ground level for a given primary energy which improves both the shower detection sensitivity and the total effective area. In the following we mention only the main points, a detailed description of the various effects to be considered can be found for example in [14].



(a) Air shower evolution

(b) Energy reaching ground level

(c) Muons vs. EM component

Figure 4: Development of a 100 TeV gamma-ray induced air shower illustrating the effect of increasing the altitude of the detector (left, from [14]). The energy reaching ground level as function of the detector altitude for proton (blue) and gamma-ray (red) induced air showers of different energies (right top, from [16]). Discrimination between proton (blue) and gamma-ray (red) shower using the number of muons and the energy in electromagnetic cascade at ground level (right bottom, from [16]).

2.1.1 Location of the observatory

With HAWC being located on the Northern Hemisphere, a next generation, large FoV gamma-ray observatory should be located in the south to allow for an all-sky coverage. A location in the Southern Hemisphere also allows to fully exploit the synergies with CTA, provides access to the central region of our Galaxy with its wealth of known high-energy gamma-ray sources including the first (and only) known cosmic ray accelerator reaching PeV energies [15]). Several plausible sites in South America are currently under investigation. E.g.:

- Argentina (Alto Chorillos, Puna desert): site at 4800m with existing infrastructure (e.g. the Large Latin American Millimeter Array (LLAMA) and as potential site for QUBIC) and a close-by small town, San Antonio de los Cobres, at 30km), with hotels, workshops, etc.

- Bolivia (Chacaltaya): site at 5200m with some existing infrastructure (e.g. the Chacaltaya Cosmic Ray Laboratory) and only 30km from La Paz, which has an international airport. However, there is no sufficiently large plateau at the highest altitude but a saddle at 5000m to the East may be large enough.
- Chile (Atacama desert): near the site of the ALMA (Atacama Large Telescope Array, at 5000m) and close to the ACT (Atacama Cosmology Telescope), several large plateaus are available with altitudes ranging up to 5430m. The site of ACT is 47km from San Pedro de Atacama, which houses the ALMA Operations Support Facility (base camp) at 2900m.

2.1.2 Detector altitude

Increasing the altitude is one of the main handles to improve the detector sensitivity, effective area and to lower the energy threshold. The main effect is the increase of shower particles at ground level as illustrated in Fig. 4a. Recent detailed Monte Carlo simulations quantify these effects [16] and pave the way for detector optimizations. As example, Fig. 4b shows the total energy reaching ground level as function of the detector altitude for different primary particles and energies.

The benefits of a higher detector site have to be balanced by the increasing difficulties to install and operate an observatory at very high altitudes. For example, low oxygen levels prohibit long-term manual labor. It is therefore foreseen to mount the detector units down the mountain and brought up largely complete. In addition access to water may be difficult for some sites and freezing of the water tanks may have to be dealt with. The expected higher rates have to be taken into account in the design of the readout and trigger electronics and/or the design of the tanks and the array (e.g. larger number of smaller tanks with local coincidence readouts).

2.1.3 Pre-existing infrastructure and support

A road nearby the site is needed for the transport of the detector components and especially the water for WCDs. Typically a nearby source of water for purification at lower altitude simplifies logistics. Some of the potential sites house already an observatory which may imply the presence of core facilities such as

- power grids or access to Diesel for generators
- network access for data transfer, remote operation and monitoring
- accommodation for "local crew" (typically at lower altitude)

Another aspect of the site selection is the national interest and funding: if the host country can contribute intellectually, materially or financially, this would obviously facilitate the installation and is an important point to be taken into account.

2.1.4 Detector area

Increasing the footprint of the detector would naturally improve the shower detection sensitivity and the available event statistics. The HAWC observatory covers about 20,000 m^2. The same amount, but not much more, of roughly level ground is available at most of the high altitude site in the Southern Hemisphere mentioned above.

2.1.5 Gamma-Hadron separation

Although interesting for cosmic ray studies (see Sec. 1.2), air showers induced by hadronic cosmic rays constitute the main background for VHE gamma-ray astronomy. It is therefore of prime importance to be able to discriminate them from gamma-ray events. With a single detector technology like the water tanks in HAWC, this discrimination is usually based on the shower topology (ground particle footprints of hadronic showers being less smooth due to muon dominated sub-showers created with high transverse momentum with respect to the shower axis). Hadronic showers could also be identified thanks to the significantly increased number of muons with respect to gamma-ray induced cascades. This difference is illustrated in Fig. 4c and several ideas and detector concepts are currently under discussion:

- scintillators either inside or underneath the WCD (e.g. ALTO, see Sec. 2.4.1)
- shielded/underground scintillator based detectors complementing the WCDs
- dividing the WCD into a top (electromagnetic+muon) and bottom (muon dominated) segment
- muon counting in the WCD (e.g. [17])
- boron-laced plastic scintillators detecting the neutron backsplash from hadronic showers hitting the ground
- ...

All proposed hybrid designs provide significantly improved suppression of the hadronic background leading directly to increased gamma-ray rates available for analyses. On the other hand they increase the cost of both the initial installation and the maintenance of the observatory, considerations that will have to be compared to a design with an increased number of simple WCD detectors.

2.1.6 Particle detection sensitivity

Increasing the detection efficiency of the individual detectors requires either increasing the light yield in the water and/or collecting more of the produced photons. The first solution might be achieved by adding a scintillating component to the water, a solution that might at the same time help prevent freezing. Collecting more photons would for example be possible with the installation of more photomultipliers (increasing the cost), use of reflecting bladders (worsening the time resolution) or the installation of a web of wavelength-shifting fibers dispersed through the water and light-piped to PMTs (increased complexity and cost).

2.2 Synergies with KM3NeT

The new gamma-ray observatory will have significant synergies with other major high-energy astroparticle observatories, KM3NeT and CTA.

After more than 10 years of successful operation the ANTARES neutrino telescope will soon be superseded by KM3NeT. KM3NeT will be particularly sensitive to multi-TeV neutrino sources within our Galaxy and thus be able to monitor the Southern Sky with unprecedented sensitivity and would be a perfect partner for a Southern TeV gamma-ray observatory.

Since the dawn of gamma-ray astronomy thirty years ago, more than 150 astrophysical sources able to accelerate particle to above TeV energies have been discovered. Unfortunately these observations are usually not sufficient proof for the presence of accelerated hadronic cosmic rays as gamma-ray radiation can also be induced by accelerated electrons (via Bremsstrahlung or inverse Compton scattering of low energy photons). For most detected gamma-ray sources, both leptonic (accelerating mainly electrons) as well as hadronic (accelerating predominantly hadronic cosmic rays) models are able to explain the observed emission. Attempts to distinguish between these competing explanations are usually based on the spectral shape of the GeV-TeV emission compared to phenomenological predictions.

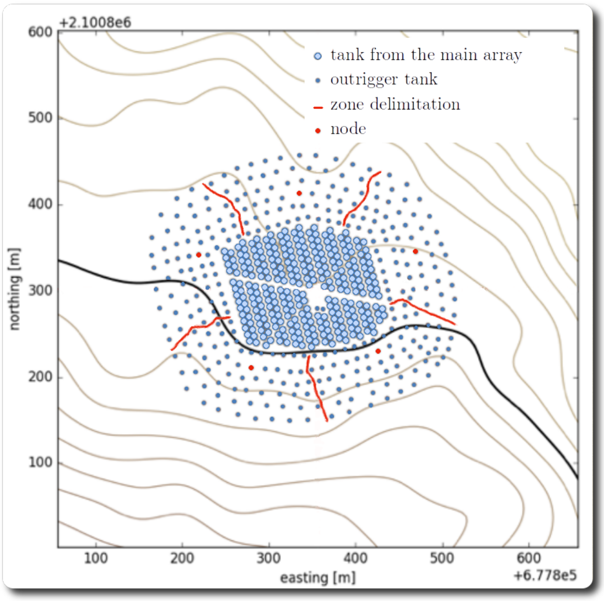
Over the last years it has become more and more obvious that joint analyses and cross-correlations between gamma-ray and neutrino observations are necessary to improve our understanding of the detected sources. Provided appropriate conditions of the environment of cosmic accelerators (e.g. magnetic fields, matter and field densities, etc.), high-energy (hadronic) particles are potentially undergoing interactions with matter and radiations fields within and/or surrounding the acceleration sites. The light mesons, predominately pions, created in these interactions will decay by emitting both high-energy neutrino as well as gamma rays. For sources where the matter and radiation fields are not too dense to cause absorption of the emitted gamma rays, we can therefore hope to find spatial and temporal correlated emission of both messengers.

Coincident information from a sensitive neutrino telescope like KM3NeT covering the same region of the sky as the next generation gamma-ray observatory will therefore greatly improve the understanding of the discovered gamma-ray sources. Inversely, neutrino telescopes are able to enormously improve their sensitivity by using external information on the source locations and source variability. Especially the latter, searches for transient emission in various wavelengths and messengers, has the potential to revolutionize the field of high-energy astrophysics over the next years. The information on transient activity in the TeV (e.g. AGN flares, Galactic binary outbursts, etc.) could be provided by the proposed new gamma-ray observatory and thus significantly enhance the science reach of KM3NeT.

2.3 Synergies and complementarity with CTA

The next generation of imaging Cherenkov gamma-ray detectors is currently entering its construction phase. The *Cherenkov Telescope Array (CTA)* will consist of telescopes with three different sizes located on two sites, one on each hemisphere. The Northern site is located on the island of La Palma at the Instituto Astrofisica de Canarias Observatorio del Roque de los Muchachos. The Southern site is less than 10 km southeast of ESO's existing Paranal Observatory in the Atacama Desert in Chile.

Similar to the increase of sensitivity provided by CTA over the current generation of IACTs (H.E.S.S., Veritas and MAGIC), a next generation, large FoV gamma-ray observatory should match the sensitivity and directionality of CTA. Current design studies show that the goal of a "Finder-Scope" for CTA is well within reach. The capabilities of such an observatory would be extremely beneficial for monitoring the VHE gamma-ray sky, triggering deep CTA



(a) HAWC: high energy extension

(b) FALCON electronics

Figure 5: The high energy extension of the HAWC observatory: the extended layout including the additional outrigger WCDs (left) and one of the Flash-ADC based outrigger nodes installed at the HAWC site (right). From [19]

follow-up observations in case of interesting events like AGN flares, binary outbursts, new transients, etc., and thus increasing the science output of both observatories.

One of the Key Science Projects is the long-term monitoring of AGN comprising short snapshot-like observations of pre-selected sources in regular intervals over the full lifetime of CTA (e.g. [18]). Although requiring integrations over somewhat longer timescales, the sensitivity of the proposed high-altitude water Cherenkov instrument could be sufficient to complement or partially take over these programs, thus freeing time for other CTA projects.

2.3.1 Usage of CTA electronics

The readout and trigger electronics of an array of water-Cherenkov detectors have a lot of similarities with electronics being developed for the cameras on Atmospheric Imaging Cherenkov Telescopes. With the Cherenkov Telescope Array (CTA) currently being under development, high performance and cost efficient readout and trigger electronics are becoming available.

FlashCAM based electronics: The HAWC gamma-ray observatory is currently taking advantage of this development and is utilizing the readout and trigger electronics that is developed for the FlashCAM (a proposed camera solution for a mid-size telescope of CTA) for the high energy extension of the observatory [19]. This high energy extension of the HAWC observatory will consist of 350 relatively small Water-Cherenkov detectors each holding 2500 liters of water. They are arranged in a sparse array with 15 meter spacing surrounding the main array of the observatory (cf. Fig. 5a). Each WCD tank contains an 8-inch PMT, which is readout with the Flash-ADC board developed for FlashCAM. The signals from the 350

WCD's are collected in five nodes spread over the array. Each node has a crate containing 3 Flash-ADC boards, which can digitize 24 channels with a sampling speed of 250 MHz at 12 bit accuracy. Full waveforms, with configurable length (typically 40 samples i.e. 160 ns), are read out and processed further for charge extraction and signal timing. At the moment, mid-August 2016, the first of these nodes has been deployed and is successfully recording air shower data (cf. Fig. 5b). The completion of the full outrigger array is foreseen early 2017, and provides an excellent testbed for testing the full waveform readout capabilities for water-Cherenkov detectors in a gamma-ray observatory.

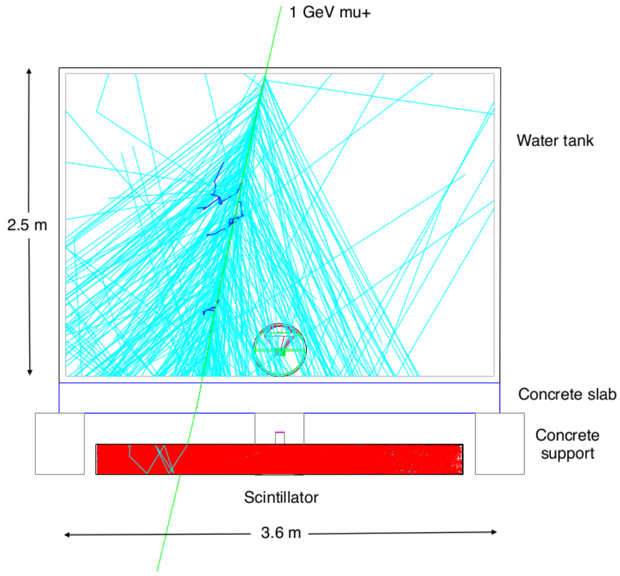
A fully digital design such as FlashCAM implies that the signals from the PMTs are digitized locally to avoid analogue signal transmission to the nodes through long cables. Since the trigger is performed in the nodes, large amount of data have to be sent there before triggering.

NectarCAM based electronics: An alternative possibility would be to use a Nectar based electronics, which has also been developed for CTA. The Nectar chip [20] has an analogue memory of 1024 cells. It operates at a sampling frequency between 500 MHz and 2.2 GHz. The trigger signal is provided by a separate path. Only when a trigger occurs is the signal digitized with a 12 bit accuracy and sent to a node (within CTA a camera server) for event building. The analogue to digital conversion is performed by the Nectar chip. The data bandwidth between the tanks and the nodes would thus be drastically reduced. The Nectar chip is currently used by the H.E.S.S. upgraded cameras and the NectarCAM camera for CTA [21]. It is an upgrade of the ARS chip which is used for ANTARES. Read-out windows of up to 60 cells are used on NectarCAM, with an analogue bandwidth larger than 250 MHz. Assuming chip operations at 500 MHz, waveforms up to 120 ns could be read out. A Nectar-based readout is being considered for the ALTO design (cf. Sec. 2.4.1).

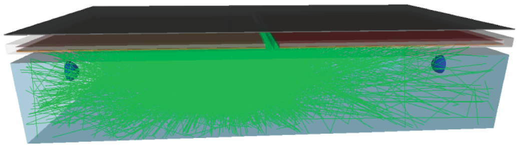
Timing and triggering: Another key element for any high altitude water Cherenkov observatory is the time distribution and trigger system. Here we could again benefit from technical developments which are being made for CTA, namely the use of the "White Rabbit" (WR, [22]) timing distribution system. In WR, a central clock is distributed over a hierarchical network of fibre-optic cables. The WR system automatically calibrates and corrects in real-time for the travel time within the fibers. Within the CTA consortium, a compact and robust integrated card is being developed which can accurately time-tag (to better than ns precision) any input trigger and transmit these time stamps – over the same fibre-optic cables and switches that are used for the timing distribution – to a single processor in the central Data Acquisition farm.

The laboratory and field experience gained within the Tunka-HiSCORE gamma-ray observatory has demonstrated that WR fulfills all requirements for precise timing in next generation experiments like CTA or a high-altitude observatory as outlined above [23].

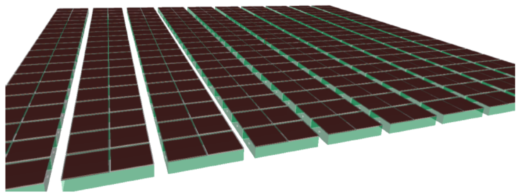
The ALTO proposal (cf. Sec. 2.4.1) is to time-tag each individual detector station trigger (for both WCDs and Scintillator detectors) and to send all time-stamps to a central processor. In this processor the search for a temporal coincidence in neighboring WCDs can be carried out, even while the front-end electronics (e.g. the Nectar chips) are being read-out, and a simple plane wavefront fit can essentially eliminate all random coincidences, and allow to identify all detector stations associated with the shower. Since the fit needs to be made for the observable sky, it may be necessary to parallelize these calculations for different patches of sky on different processors, perhaps also exploiting GPUs. The data from tanks which are not in coincidence can then be rejected, so reducing greatly the data which need to be stored to only those which correspond to physics events.



(a) ALTO



(b) single RPC-WCD



(c) LATTES array

Figure 6: Different designs currently under study for a VHE gamma-ray observatory using hybrid designs combining water Cherenkov detectors with scintillators (left, ALTO Design, [25]) and RPCs (right, LATTES design, [26]).

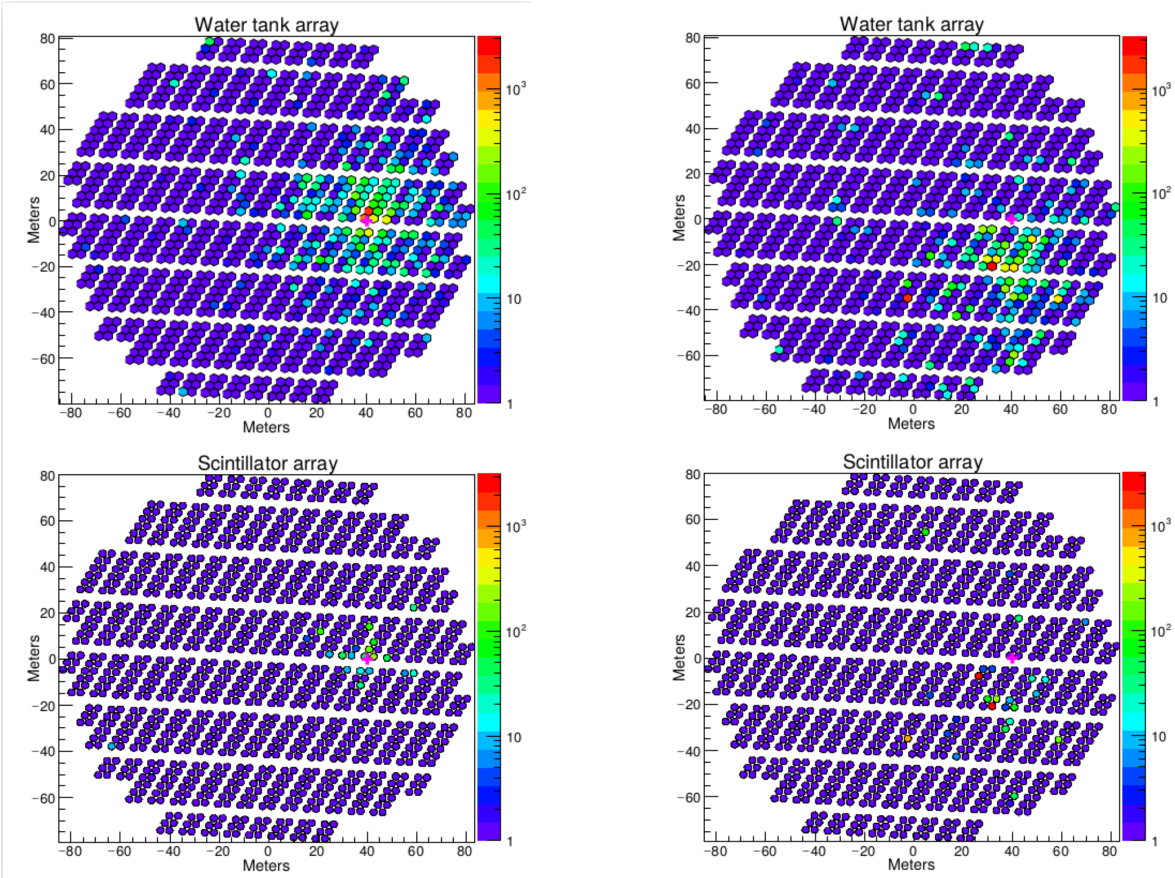
2.4 Design studies

Based on the general outlines given above (cf. Sec. 2.1), several designs of hybrid detectors are currently under detailed investigation. These *hybrid designs* typically combine WCDs with additional detector concepts to either improve the gamma-hadron separation and/or the precision of the air shower reconstruction. As illustration, two of these conceptual designs are discussed in the following.

2.4.1 ALTO

ALTO is the name given by the Astroparticle Group at Linnaeus University (LnU) to a project to build a wide-field Very-High-Energy (VHE) gamma-ray observatory at very high altitude in the Southern hemisphere, with smaller water Cherenkov detector (WCD) tanks than those used by HAWC, the addition of a scintillator layer detector (SLD) below the WCD tank and precise read-out electronics and timing distribution based on White Rabbit (cf. Fig. 6a). The construction of smaller tanks with respect to HAWC will allow to have a finer-grained view of the shower particles on the ground, which should help in the rejection of hadronic backgrounds. The current design of the ALTO water tank is hexagonal, so as it can be close-packed into "clusters" of 6 tanks, with access from the sides. The full ALTO observatory would be formed by about 1000 of individual stations (cf. Fig. 7).

ALTO water-Cherenkov channel: The water-Cherenkov tank is hexagonal (3.6 m flat-to-flat diameter, 2.35 m height), placed on a 30 cm thick concrete table – more than required for rigidity and acting as an absorber for electrons – supported on 5 circular concrete feet of 60 cm height. Cherenkov photos would be detected by a single photomultiplier tube, ideally one ANTARES OM, placed at the bottom of the tank.



(a) Gamma-ray (b) Proton

Figure 7: Example of the response of the ALTO array to a gamma-ray or proton (left / right respectively) of energy 1.5 TeV, zenith angle 12° and impact parameter at 40 m along the x-axis (marked by the pink cross). The WCD / SLD response is shown on the upper / lower plots. The color scale is in photoelectrons. Note particularly that the SLD response to the gamma-ray shower is only due to electrons near the core, whereas for the proton shower several more distant signals from muons are identifiable. From [25]

ALTO scintillator channel: The scintillator layer detector is a cylinder of polyethylene or aluminum positioned below the WCD (either on the ground or on rails suspended below the concrete support) with a height of 25 cm and a diameter of 3 m. The scintillator liquid mixture that is currently being used in the simulations is the linear alkyl benzene PETRELAB 550, doped with two wavelength-shifters PPO (5 g/L) and POPOP (0.02 g/L) [24]. One important consideration for this type of liquid scintillator is that it is non-toxic, given that ALTO will be in a remote location, and that any delicate flora and fauna should be protected. Scintillation photons are detected by a 3-inch Hamamatsu R6091, placed above the center of the tank facing down.

ALTO Front-End Electronics: The ALTO design considers to use NectarCAM-type electronics, with 1 node per 6-tank cluster. In the NectarCAM camera, a “drawer" is an element of the focal plane consisting of 7 photomultipliers. For ALTO, this scheme could be used with minor adaptations, with one drawer electronics being used for the WCDs, and a second for the SLDs. The modifications needed would be essentially on the read-out and trigger logic, especially to allow a read-out only of those channels which have triggered, rather than all channels as for CTA. For the WCDs, a local per-tank trigger of a few photoelectrons should greatly reduce the main backgrounds from dark counts (shot noise) and ^{40}K in the glass of the Antares modules (cf. Sec. 4). The true trigger rate from local muons and showers at the planned altitude is estimated to be < 20 kHz. Note that the read-out dead-time for the Nectar chip is 1.9 μs (6.5 μs) for 16 (64) sample readout, so reading at this rate causes a dead-time of 4 or 11% respectively. For the SLDs, a lower rate is expected, leading to a lower dead-time.

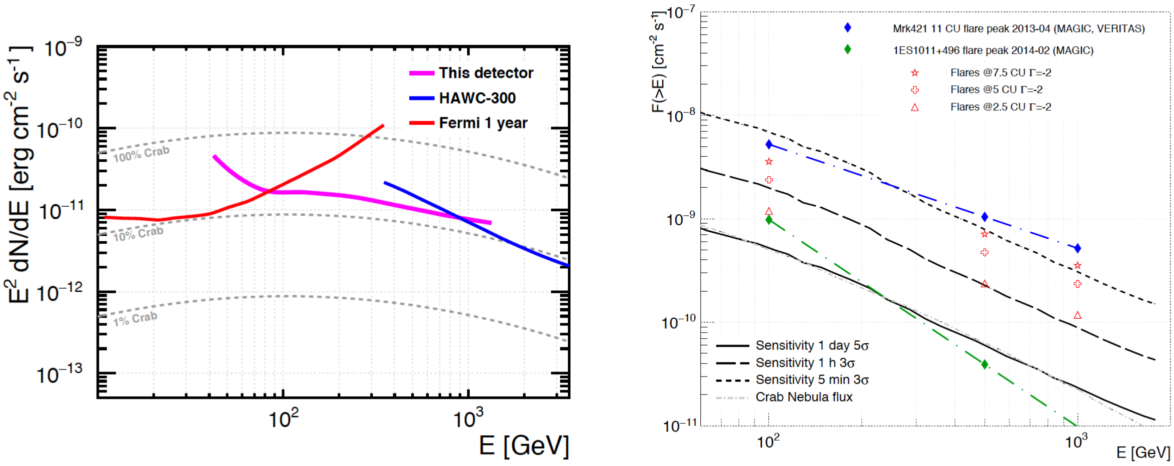
In summary, using available NectarCam electronics with minor modifications, an operational ALTO read-out (with some dead-time) could be produced. Further electronics developments, e.g. the DREAM chips under development at IRFU/Sedi, could provide a practically dead-time-free system. Given the expected rates, the waveform data can be sent from the full cluster of WCD + SLDs over a single 10 Gbps optical fibre to a central data-acquisition farm, where they can be buffered in memory while awaiting a temporal coincidence decision. The trigger decision as well as the distribution of the necessary clock information is available with ns level precision using the White Rabbit system described above (cf. Sec. 2.3.1).

ALTO Technical Design Conclusions: The above developments will allow a distributed electronics front-end per cluster, with the transmission of digital information over fibre-optic cables to the central DAQ, with one fibre for the White Rabbit timing information and one other fibre carrying the integrated charge and time-of-maximum information from the PMTs, using standard Ethernet protocol and switches and going to a server farm for buffering while awaiting the timing-coincidence information. Note that using fibre optics for the data/timing transmission provides full lightning protection. If combined with power provided by a solar-panel/battery setup as used in the Pierre Auger Observatory each base-element would be completely electrically isolated, but otherwise surge protection being needed only for the low-voltage power supply (12V or 24V) for each tank.

ALTO Simulations: The astroparticle physics group at Linnaeus University is carrying out Monte Carlo simulations of the proposed ALTO design. These include CORSIKA simulations of gamma-ray and proton showers in the atmosphere, full GEANT4 simulations of the detection elements, interactions of particles in water and in the scintillator layer and photon collection in the photo-multipliers. In Fig. 6a the response of an ALTO station to a simulated 1 GeV muon track (green) is shown. Cherenkov photons are shown in light blue and Scintillation photons in red.

Background rejection and Sensitivity: In the ALTO design, the scintillator layer is very important in order to be able to “tag” the passage of muons, which are the almost unambiguous signature of the nature of the particle cascade, as proton-initiated showers are muon-rich. The implementation of this new “muon-tagging” will allow to increase the signal over background discrimination and thus allows an increase of the sensitivity. An illustration of the signals generated by a gamma ray vs. proton shower in both the WCD and the SLD is shown in Fig. 7. For gamma ray induced events the SLD signal is dominated by leakage of shower electrons and therefore concentrated around the shower impact position, whereas for proton showers the muons generating such signals are much more widely dispersed.

Exploiting these features and using an extensive set of simulations covering the full range of energies and zenith angles, the development of background rejection parameters is currently under development.



(a) LATTES: differential sensitivity

(b) LATTES: transient performance

Figure 8: Performance of a hybrid detector design combining RPCs and WCDs. Differential, time integrated sensitivity in comparison with Fermi-LAT and HAWC (left) and sensitivity to transient events in comparison with past flares of Mrk421 and 1ES1011+496 (right). From [26]

2.4.2 LATTES

Another design idea for a large field-of-view gamma ray observatory has been proposed recently by P. Assis et al. [26]. In this hybrid concept, called LATTES, two techniques that have been used successfully independently in the past are combined:

- A high resolution, position sensitive detector based on Resistive Plate Chambers (RPCs), following the ARGO-YBJ detector [27]
- A water Cherenkov detector with smaller tanks compared to HAWC.

The detector is covered by a thin, 5.6 mm, layer of lead, to allow conversion of photons in the air shower to convert into electron-positron pairs and thus increase the detection efficiency. The increased sensitivity to shower-photons is also enhancing the reconstruction accuracy of the shower direction and thus the incoming direction of the primary particle. The design is illustrated in Fig. 6b.

The relatively small individual detector cells have a horizontal surface of 3 m $\times$ 1.5 m and a height of 0.5 m. They are then placed in a dense grid covering about 10,000 m^2 with detectors placed in rows, i.e. detectors touching each other at the long side and a small spacing of about 0.5 m between them on the other side for maintenance purposes. See Fig. 6c for an illustration. The proposed RPCs are derived from developments done within the Pierre Auger Collaboration and are characterized by a low gas flux, 1-4 cc/min, and their, compared to other RPCs designs, low price. The design is robust and has been successfully tested in the harsh outdoor environment at the site of the Pierre Auger Observatory (Malargüe, Argentina).

The outlined detector has a low energy threshold around 100 GeV, good sensitivity and a large field of view. The differential sensitivity of the studied detector configuration (requiring $N_{\text{excess}}/\sqrt{N_{\text{bkg}}} = 5$ and $N_{\text{excess}} > 10$) is shown in Fig. 8a. The shown figure has been derived for one year of operation and (conservatively) assuming a 40 % duty-cycle.

Another example is the sensitivity to transient phenomena. The outlined detector would, without external triggers, for example be able to detect several GRBs per year, providing detailed light-curves with tens to a few hundred photons. As illustration, Fig. 8b shows the integral sensitivity for several time periods ranging from 5 min to 1 day. For reference the exceptionally bright flare of Mrk421 in 2013 and a weak flare from 1ES1011+496 (02/2014) are shown as well. In conclusion, as long as the flare lasts for more than a few days, even weak flares will be detected.

3 AMIGO: Antares Modules In a Gamma-ray Observatory

We, the signatories listed above, propose to use the optical modules of the ANTARES neutrino telescope within a next generation high-altitude water Cherenkov observatory.

The science case for such an observatory is robust (cf. Sec. 1.2) and the baseline technology has been proven by the Milagro and HAWC experiments. Whereas the overall cost of high-altitude water Cherenkov observatories is small compared to the Imaging Air Cherenkov technique, a next generation experiment would still require substantial amounts of funding if build "from scratch" (see below Sec. 5). As successfully demonstrated by HAWC by re-using the PMTs (and the electronics) of the Milagro experiment, significant cost reductions can be achieved by re-using previous equipment. We firmly believe that the availability of the ANTARES optical modules for a water Cherenkov gamma-ray observatory would constitute a phenomenal boost for the project itself and, given the current rarity of new projects, the field of astroparticle physics as a whole.

4 The ANTARES optical modules

The ANTARES telescope Cherenkov light detection is based on 885 optical modules operated in the sea water at a depth greater than 2000 m and a constant temperature of 13.3 °, which have been immersed between 2006 and 2008. After 8 to 10 years of operation, a large fraction of the optical modules is still operational. Below is a brief description of some optical modules characteristics, more details being available in [28] and [29].

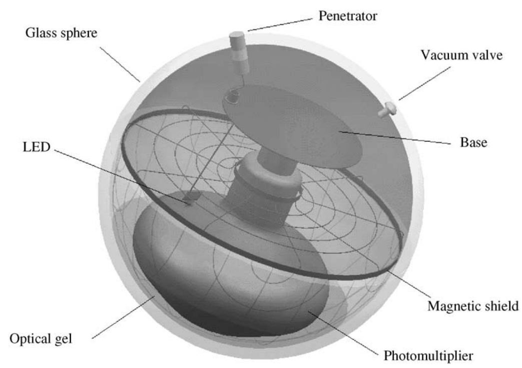
The optical module consists of a pressure resistant glass sphere housing a photomultiplier and its base, and the necessary connection through a penetrator linked to a 1 m long cable equipped with a SubConn IL12M connector from MacArtney Underwater Technology. An image and a schematic view of the module is shown in Fig. 9.

The photomultiplier is the 14-stage 10 inch hemispherical tube from Hamamatsu type R7081-20 with the following characteristics:

- photocathode area 500 cm^2
- quantum efficiency 20 % and collection efficiency > 80 %
- transit time ~ 70 ns and transit time spread below 3 ns. The transit can be monitored with a flashing blue LED glued on the rear part of the bulb
- DC powered active base from iSeg Technologies Germany GmbH, applying a focusing voltage of 800 V between photocathode and first dynode, and amplification voltage up to 1600 V spread from first dynode to anode
- overall operating voltage from 1600 V to 2000 V for the required gain of 5 x 10^7, resulting in 8 pC signal for a SPE integrated over the typical pulse duration of 25 ns
- dark count rate below 2 kHz at 1/3 SPE threshold without glass sphere

The glass sphere is the 17 inch Vitrovex 8330 from Nautilus Marine Service GmbH qualified up to 700 bar. In the front hemisphere, the PMT is coupled to the glass with transparent optical gel in which a μ-metal cage is inserted to avoid degradation of the PMT TTS due to

(a) photograph



(b) schematic view

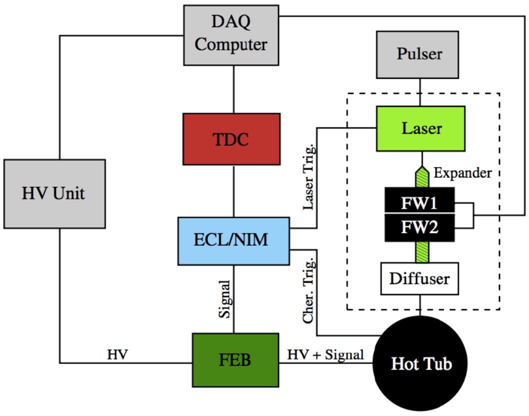
Figure 9: The optical module of the ANTARES neutrino telescope. A picture showing the complete module in the foreground and an open sphere in the back (left). The left plot illustrates the main component of the module, from [29].

the Earth's magnetic field. The black painted back hemisphere is equipped with the penetrator and a vacuum port to evacuate the sphere during closure in order to avoid its opening at external atmospheric pressure, and a manometer to monitor the internal underpressure (typically 200 mbar). The sphere is closed simply by putting the 2 hemispheres in front of each other and sealing the equatorial seam with rubber sealant protected by 2 turns of sealant tape. Due to the presence of ^{40}K in the glass, the dark count rate of the PMT mounted in the glass sphere is about 3 kHz. This was not an issue in ANTARES since the baseline counting rate at 1/3 SPE threshold of the optical modules in the deep sea water is around 60 kHz due to ^{40}K of the sea water and bioluminescence.

The cables of the optical modules are linked to the front end electronics in a titanium container via BH12F sockets from MacArtney Underwater Technology. The signals transmitted are:

- IN: 48 V DC power to the active base
- IN: low voltage (0-4 V) to create amplification voltage (0-1600 V)
- OUT: low voltage monitoring
- IN: pulse (0-24 V) to flash the internal LED
- OUT: dynode 12 signal
- OUT: dynode 14 signal
- OUT: anode signal

During the 10 years of continuous ANTARES running, the PMTs gains were regularly tuned playing with the high voltage, so that the SPE would stay at its nominal value. Ageing tests performed in the lab, illuminating several PMTs well above the in-situ conditions, have shown that 10 years of running in ANTARES, even with high bioluminescence rates, will not lead to any substantial degradation of the PMT performance.



(a) schematic view

(b) photograph

Figure 10: The testbench at the Los Alamos National Lab (LANL) used to characterize the PMTs used in the HAWC observatory.

4.1 Preparatory work

4.1.1 ANTARES-OM testing @ HAWC

In preparation of the AMIGO project, two ANTARES modules available at Irfu/Saclay have been sent to the HAWC group at Los Alamos National Lab (LANL) in August 2016. LANL has a PMT testing facility in which the 900 Hamamatsu R5912 8″ diameter PMTs and the 300 Hamamatsu R7081-HQE 10″ diameter PMTs used in the HAWC observatory have been characterized (cf. Fig. 10). A data acquisition system that can measure charge and timing is available and will be used to characterize the ANTARES modules in conjunction with the standard HAWC readout as well as with the the FlashADC based readout used for the HAWC outrigger array. A pulsed laser with a multi position filter wheel to vary the light levels on the PMTs over 6 orders in magnitude will be used during the test. A unique feature of the LANL test facility is the availability of a Cherenkov light sources made by a beta source imbedded in non-UV absorbing acrylic. Applying the same testing procedure, the R7081 PMTs from ANTARES will be compared to the standard HAWC PMTs. Measured characteristics include gain vs high voltage, after-pulsing, pre-pulsing, linearity vs light level, and relative efficiency to the spectrum of Cherenkov light. Results of these tests are expected in autumn 2016, i.e. after the installation campaign related to HAWC high-energy extension taking place in August/September.

Most of the HAWC R5912 PMTs were purchased in the mid 90s and have already been used in the MILAGRO observatory. They only show slight degradation relative to newer PMTs. That leads us to believe that the ANTARES PMTs remain a very valuable resource that can be used in a future detector such as one similar to HAWC in the Southern Hemisphere.

4.1.2 ALTO prototype

The LnU group is working with a group of companies in the region to build a prototype tank on the LnU Växjö campus. Strength calculations for a carbon fibre design of the tank are ongoing. Two spare ANTARES modules, contributed by CEA-DSM/IRFU, are already available for installation and tests. The full prototype is expected to be ready and installed in Spring 2017. Discussions for the use of one of the NectarCam early prototype drawers will proceed in parallel, with the groups involved in the NectarCAM drawer electronic (CEA-DSM/IRFU and LPNHE, Paris).

Funding for the prototype (investment cost, plus one full-time post-doc) has been obtained from Swedish private foundations. For further funding, several funding applications are ongoing with responses expected for the end of 2016, while other funding opportunities will be open for application in 2017.

The prototype measurements on the full single WCD + SLD will provide the rates for the triggering from showers, local muons, and backgrounds as a function of trigger thresholds, which can then be extrapolated to very high altitudes. We expect that final "singles" rate for the high-altitude WCD, as extrapolated from HAWC, should be 10–20 kHz for ALTO. For the scintillation volume, scaling from other scintillator experiments gives us an estimate of $\sim$ 1 kHz for ALTO. These rates are all compatible with the operating mode proposed for ALTO. In addition, as an in-depth test, we have a number of ~ 1.5 m^2 scintillator tanks which were used for the surface detector array temporarily deployed around the ANTARES site, kindly provided by J.P. Ernenwein. We plan to use this detector array in parallel with the tank prototype to tag muons traveling in specific paths through the detector, which should provide us with a characterization of the response of the 1-tank set-up to muons a a function of zenith angle, which can be used as a check on the simulations and a verification of the detector response.

5 Timeline, Budget and implementation

At the current stage, the timeline of the project to build a high-altitude water Cherenkov observatory in the Southern Hemisphere is still subject to substantial uncertainties. A whitepaper describing the observatory is in preparation. Publication is planned in time with the 35th ICRC in summer 2017. A workshop bringing together all interested parties is organized in Puebla (Mexico) in November 2016 [30].

A rough indication of the total cost of the project can be derived from the cost of the construction and commissioning of the HAWC observatory which amounts to about $15 M, funded by several agencies from the US and Mexico. Assuming a baseline design of WCDs similar to the ones used within HAWC, a similar total cost can be expected for a Southern Hemisphere observatory of the same size. It should be noted that each of the detector parameters outlined in Sec. 2.1 is directly influencing the total project cost. As mentioned, none of them has been fixed so far.

Concerning the implementation of the proposed AMIGO project, we propose the following steps for the near future:

- agreement of the ANTARES Collaboration to use the ANTARES optical modules in a next generation high-altitude water Cherenkov observatory
- definition of a non-destructive decommissioning operation of the ANTARES detector, i.e. keeping the OMs, the penetrators and the connected cables intact
- transport and storage of the OMs (incl. their connectors, etc.) at a nearby shore station (e.g. the Foselev instrumentation hall)

The signatories of this proposals are available to support the outlined program and, if deemed necessary, participate in the foreseen recovery and storage operations. Especially on-shore activities like cleaning, sorting and preparations for the storage of the recovered optical modules could be handled by volunteers among the signatories.

Whereas all members of the ANTARES collaboration are invited to participate in the next generation high-altitude water Cherenkov observatory outlined above, the agreement of re-using the ANTARES optical modules in such an experiment would also create unique links between this new observatory and the successor of ANTARES, the KM3NeT neutrino telescope. As briefly outlined in Sec. 2.2, the science reach of both experiments would benefit from this deep partnership. Thanks to this special relation between the two experiments, to be implemented for example via the exchange of data and joint data analyses, one would create the first truly global multi-messenger observatory, enabling exciting discoveries and breakthroughs in high-energy astro(particle) physics.

Acknowledgements

The presented AMIGO proposal has been made possible and improved during numerous discussion with a large number of colleagues. All have expressed their support for the proposal and are listed in the *Expression of interest* section at the beginning of the document. Fabian Schüssler thankfully acknowledges direct contributions to the text and the figures from Brenda Dingus (LANL), Michael DuVernois (Madison), Harm Schoorlemmer and Armelle Jardin-Blicq (MPIK), Jean-François Glicenstein and Bertrand Vallage (Irfu), Yvonne Becherini and Satyendra Thoudram (LnU) and Michael Punch (APC, LnU).

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