PROCEEDINGS OF SCIENCE

The Mercedes water-Cherenkov detector: a multi-PMT shallow tank design proposal for ground-based gamma-ray observatories

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We present the concept of a shallow, single-layer, multi-PMT water Cherenkov detector (WCD) unit for ground-based gamma-ray astronomy. The design was developed as part of the R&D activities for SWGO, as a candidate WCD unit solution for the future Observatory. The main objective of the proposal is to achieve a low-volume single-layer surface detection unit with good calorimetry and timing of the shower front, and excellent gamma-hadron discrimination capability. The unit name, Mercedes, is derived from its configuration, where 3 PMTs are positioned equidistant from the center of the unit in a 120° symmetric azimuthal arrangement. Background rejection, in the TeV range, is based on the asymmetric illumination of the PMTs by energetic muons traversing the water volume. The mechanical implementation is based on rotomolded tanks similar to those used in the Pierre Auger Observatory. For easy deployment, the PMTs may be installed through openings in the lateral walls of the tank, and placed outside water, observing the calorimetric volume through transparent windows in the tank bladders. The highly innovative tank proposal, whose production technique is already patented, and at the commercial stage, has a jacketed-wall structure that houses all electronics and cabling, and a layer of insulating foam to avoid freezing at high-altitude. The mechanical concept was conceived for inexpensive production, easy deployment and maintenance, and to provide a cost-effective solution for high-altitude large array designs with several thousand units, such as in SWGO.

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1. Introduction

The window from TeV to PeV gamma-rays is crucial for understanding non-thermal phenomena taking place in the Universe. For over three decades, ground-based gamma-ray observatories have explored the cosmos through these extreme messengers, detecting a growing number of sources of different types, both within and beyond the Galaxy.

Extensive air-shower (EAS) arrays based on high-altitude water Cherenkov detectors (WCD) are now consolidated as one of the most successful technologies for ground-based gamma-ray observations, complementing the work carried out by the imaging atmospheric Cherenkov telescopes (IACTs). EAS arrays are wide-field transit instruments, allowing for the continuous survey of large regions of the Galaxy in very- to ultra-high energies (from a few hundred GeV to the PeV).

Altitude WCD arrays work by detecting the Cherenkov light produced in water by the secondary particles of air-showers. In recent years the technique has been successfully used by experiments such as the Pierre Auger Observatory [12], HAWC [1], and now LHAASO [4], for the study of both cosmic-rays and gamma-ray signals. Due to the narrowness of the shower front, that traverses the detector in nanosecond timescales, and the feebleness of the signal, fast electronics and efficient photo-detectors are required. Likewise, the technique depends on reliable methods to separate the gamma-ray signals from the overwhelming cosmic-ray background, which, at the energies of interest, can be up to 10^5 times more numerous.

The SWGO collaboration is currently evaluating a number of alternatives to the various detector elements of the observatory, including the mechanics options for the WCD designs. In addition to the rotomolded HDPE tanks, steel tanks are also being considered for the land-based array [3], as well as floating bladders directly deployed in a lake [9] or in an artificial pond [10].

In these proceedings, we present the R&D efforts conducted to develop and build a novel WCD unit concept for SWGO which can adequately respond to the experimental requirements, and is also cost-effective for the implementation of a large array of several thousand detector units deployed in altitude. The design of the so-called Mercedes WCD unit profited to a large extent from the previous experience of the Pierre Auger observatory.

2. The Southern Wide-field Gamma-ray Observatory[1]

The Southern Wide-Field Gamma-ray Observatory (SWGO), currently in the R&D phase, is a project to build the first major EAS array in the Southern Hemisphere, based primarily on the WCD technique [**?**]. It will be installed in the Andes, above 4.4 km a.s.l. [8], and will be sensitive to photons with energies from a few hundred GeV to the PeV. SWGO will open a new astronomical window into the ultra-high energy sky from the South Hemisphere, and thus complement the HAWC and LHAASO experiments, operational in Mexico and China, respectively.

SWGO will work as an efficient surveying and monitoring instrument of the extreme sky. The SWGO baseline design consists of a dense core region of closely packed WCD stations, with 320 m in diameter, and a sparse WCD outer array of at least 600 m in diameter. A number of designs have been proposed for the WCD station of SWGO, and are currently under evaluation [7].

[1] https://www.swgo.org

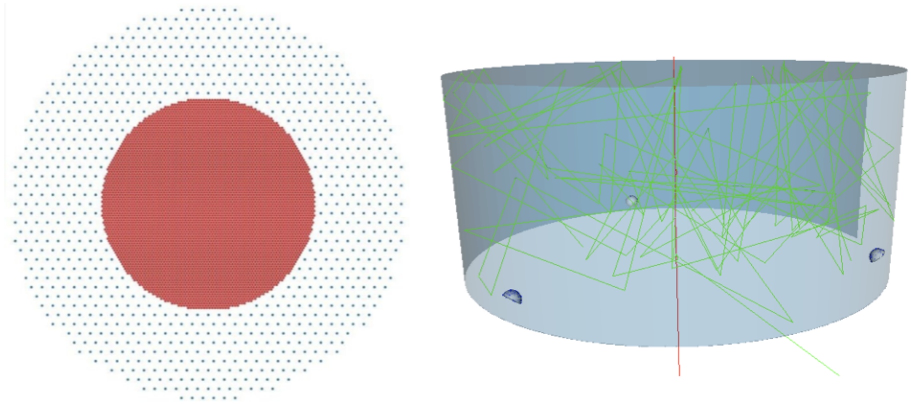

Figure 1: (Left) Illustration of the reference array configuration for SWGO showing a dense core of WCD stations surrounded by an sparse outer array. (Right) The Mercedes WCD concept design. The 120° Mercedes star arrangement, with three lateral PMT positions symmetrically distributed in azimuth (M3), is presented. For illustration, a simulated vertical muon (red track) is shown passing through the calorimetric volume and producing Cherenkov photons (green tracks).

3. The SWGO Mercedes WCD design

The Mercedes tank is a compact, shallow WCD station proposal for SWGO, with a single calorimetric chamber for measurement of the Cherenkov light. The tank encloses a light-tight, Tyvek-lined bladder, filled with 15 m^3 of purified water. The Cherenkov signal is read by multiple photosensors (PMTs) placed outside the water, and which observe the internal volume through rigid, UV-transparent windows attached to the bladders.

Figure 1 shows the geometry of the Mercedes tank. The unit dimensions, presented in Figure 3, are of 3.6 m in diameter and 1.7 m water height were chosen to maximise cost-performance and reduce water consumption. They correspond to the widest rotomolded tank that can be produced with a conventional-size oven and easily transported without special road operations. The water height, on the other hand, optimises direct illumination of the bottom PMTs by near-vertical incoming particles.

The PMT positions are pre-built in the rotomolded structure and designed for an easy installation of the photosensors, which directly connect to pre-installed unit cabling (a "plug-and-play" approach). The unit's PMT positions consist of three lateral positions symmetrically displaced by 120° in azimuth, and located at the base of the lateral walls, which give the name to the unit design. The three lateral photosensors can be installed and serviced from outside the tank, facilitating deployment and maintenance. Additionally, two central PMT positions, at the bottom and the top of the tank, add flexibility to the design configuration, allowing for optimization of the hardware to different areas of the array, while using the same WCD unit mechanics throughout (see Table 1).

The performance of the Mercedes design was simulated in [2]. The separation of the electromagnetic from the muon signal is important to improve the gamma/hadron air-shower discrimination. In the core array region, and optimised for the lower energy range of operation, down to a few hundred GeV, the multi-PMT configuration (M3) allows for an optimal light collection from low-energy showers. In the outer array, and optimised for showers of energy greater than a few TeV,

Acronym	Description	Preferential Usage
M3	3 bottom 8" PMTs on a 120^o star configuration	Array region optimised for 100 GeV-5 TeV
C1	1 central bottom 8" PMT	Array region optimised for 5 TeV - few PeV
M3T1	3 bottom 8" PMTs on a 120^o star configuration + 1 small 3" central top PMT	Units grid to improve angular resolution and minimise saturation
C1T1	1 central bottom 8" PMT + 1 small 3" central top PMT	Units grid to minimize saturation in energetic events

Table 1: The Mercedes family of WCD stations: possible PMT configurations for the shallow tank unit.

a single-PMT station (C1) is sufficient for the calorimetric measurement. For the most energetic showers up to PeV, a second small PMT could be added to minimise saturation and increase the station dynamic range (as in M3T1 and C1T1 configurations).

Gamma/hadron separation in the multi-PMT station exploit the fact that muons, present in cosmic-ray showers above a few TeV, will traverse the tank and imprint an asymmetric illumination in the upward-looking PMTs, from the direct Cherenkov light signal. An excellent gamma/hadron (γ/h) discrimination was shown in [5] to be achieved by computing the value of a global variable, $P_{\gamma\mathrm{h}}$, defined for individual showers as

$$P_{\gamma\mathrm{h}} = \sum_{k=1}^{n_{\mathrm{stations}}} P_{\mu,\mathrm{h}}, \tag{1}$$

where the sum runs over all the active stations placed at a distance greater than 40 m from the shower core. $P_{\gamma\mathrm{h}}$ is simply the sum of the probabilities of each individual selected stations being hit by a muon. The distribution of $P_{\gamma\mathrm{h}}$ for proton and gamma showers is shown in Figure 2.

Background rejection can be further improved by the use of suitable metrics exploiting the different array footprints between the cosmic- and gamma-ray induced air-showers, as is the case, for example, of the new LC_m variable developed in the context of SWGO [6], which quantifies the azimuthal non-uniformity in the shower pattern at the ground as a function of the distance to the shower core. The strength and relevance of this particular variable for SWGO, which aims to achieve excellent γ/hadron separation applying only a surface array, and without recourse to underground muon detectors, is that it represents an alternative way to access the intrinsic differences in the development of electromagnetic and hadronic showers, serving as an exact proxy to the number of muons present in the shower (see Figure 2).

4. Shallow rotomolded tanks for the Mercedes WCD design

We have designed a shallow rotomolded high-density polyethylene (HDPE) tank for implementing the Mercedes WCD design for SWGO. The concept is illustrate in Figure 3. The solution is designed to fulfill the following requirements for SWGO:

- achieve significant reduction in use of water and easy transport, by reducing WCD unit size;
- to deliver an integrated anti-freezing solution for operation at high-altitude;
- to achieve an easy and reliable deployment of the WCD unit, reducing labour in altitude;
- to reduce post-deployment intervention requirements to a minimum.

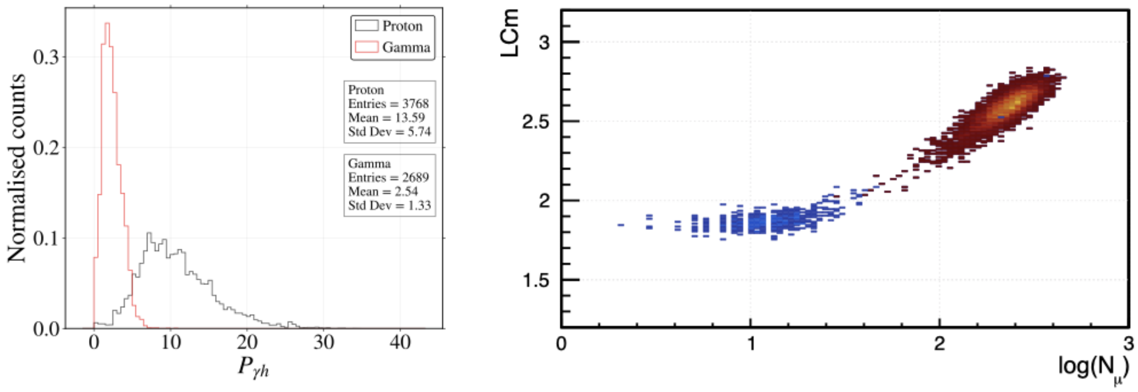

Figure 2: (Left) Distribution of $P_{\gamma \text{h}}$ for proton and gamma showers. The values of $P_{\gamma \text{h}}$ are clearly higher in proton showers. (Right) LC_m versus log N_μ distributions for gamma showers with a primary energy of about 100 TeV (blue left histogram) and for proton showers (red right histogram) with similar energy at ground.

The tank has a double-wall (jacketed) structure filled with polyurethane foam (PU), for thermal insulation. The tanks are made of a resin equivalent to Exxon-Mobil 8661 (as used in Auger), but with superior UV protection for altitude deployment and amounting to excellent mechanical properties and very low deformation.

In order to achieve light-tightness and UV resistance, pigments were added to the hot composite resin. The inner layer (interior wall) was added with 2% carbon, and the beige outer layer was added with enhanced hindered-amine light stabilizers, with a UV-30 degree of protection, which guarantees safe operations at 5 km a.s.l. for a minimum of 20 years. Both the inner (carbon black) and the outer (beige) walls have 10 mm thickness. The PU-insulated space between the jacketed walls has 10 cm thickness. The thickness of the walls is designed to withstand the specific stresses expected for the tank. Lateral reinforcements were also added along the tank circumference.

Thermal insulation is important to avoid freezing of the water in altitude, which could affect unit performance and eventually damage the Tyvek liner enclosing the calorimetric water volume. The PU-filled spacing is also used to house all the cabling of the unit photosensors and electronics, adding reliability, and allowing for pre-installation and test of the cables and connectors at the assembly building in low altitude, for a simple and speedy deployment on site ("plug-and-play").

The deployment of the HDPE tank requires minimum ground preparation, and the units can be placed directly on flattened ground. The bladder is water and light-tight, and lined with Tyvek in the interior for maximising collection of the Cherenkov light by the photosensors. Once filled with purified water, it stays tightly placed within the tank. The ceiling can withstand the weight of three adult men without collapsing or deforming. The hatchcover is made of two-colour polyethylene sheets, with the same thickness as the tank walls, and gaskets are made of polyurethane foam, serving as a light seal for the tank interior.

The shallow HDPE tank solution was developed with Rotoplastyc (`https://rotoplastyc.com.br`), the Brazilian company responsible for the production of circa 1/3 of the 1,600 Auger tanks [11]. The rotomolding technique for the jacketed-wall tanks, developed in the context of the SWGO R&D activities at CBPF, was patented by the company in 2021. The production of 2 m-diameter rotomolded tanks following this technique is already at commercial stage in agribusiness.

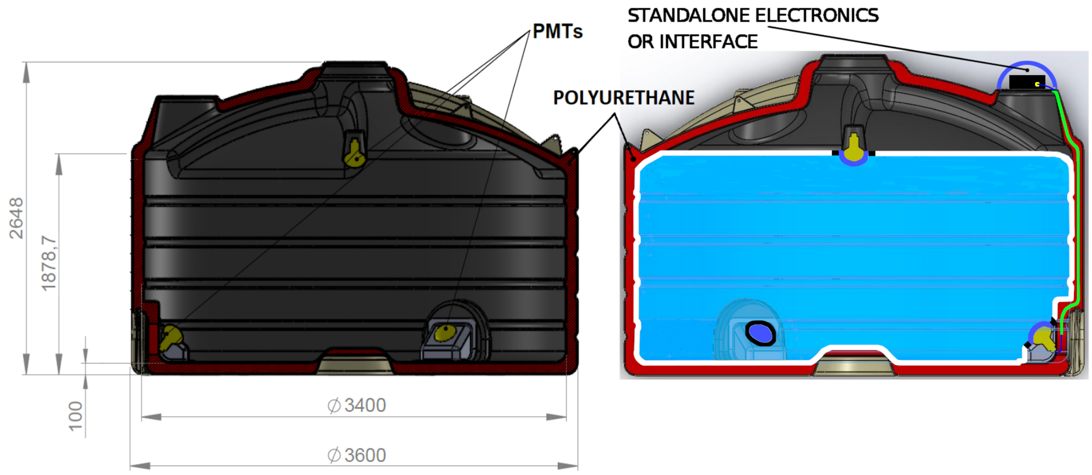

Figure 3: Rotomolded jacketed tank design. The single chamber contains five pre-molded PMT positions which can be instrumented as required, with one downward-facing top and one upward-facing bottom central PMT position, and three lateral PMT positions symmetrically distributed in azimuth – the 120° Mercedes star arrangement. The dimensions and detailed structure correspond to the shallow WCD proposal for SWGO, realising the concept of the Mercedes detector unit.

5. SWGO HDPE tank production and deployment model

Our innovative design of a jacketed-wall structure of the HDPE tank is unique in the world, involving a novel rotomolding process developed originally for SWGO, which is now patented and at a commercial stage, with the regular delivery of 2 m-diameter tanks by Rotoplastyc to the agribusiness in Brazil.

Given the bulk of the rotomolded detector units, and in order to facilitate transport, production nearby the site is desirable, and we plan to install a factory within 3 hours drive from the final array site. For all candidate SWGO sites there is a large city below 2,000 m a.s.l. that can match this production requirement. Rotomolding in altitude with the closed-oven process is regularly applied at altitudes well above 2,000 m a.s.l. for commercial applications, and therefore safe and reliable for production of the SWGO WCD units.

The jacketed tank was designed to enable what we call a "plug and play" deployment in altitude. Before injection of the insulating polyurethane foam, ducts are installed in between the double tank walls, from the three lateral PMT positions to the electronics dome housing the unit electronics, as illustrated in Figure 3. The ducts are used for passing the signal and HV cables, and connectors are installed in both ends, before the tank leaves the assembly building. Before going to the site all cabling and connections are already tested in position, reducing failures and risks during deployment. In altitude, the only remaining task is to do the PMT coupling and connections. The installation of the cabling within the PU-insulated ducts means one does not need to worry about UV resistance of the cables or temperature variations. The bladder would also leave the production unit pre-installed inside the tank.

A technical drawing of the Rotoplastyc jacketed HDPE tank is shown in Figure 4. Rotoplastyc would be able to produce 160 tanks per month at a factory nearby the site. The tank weights circa 1

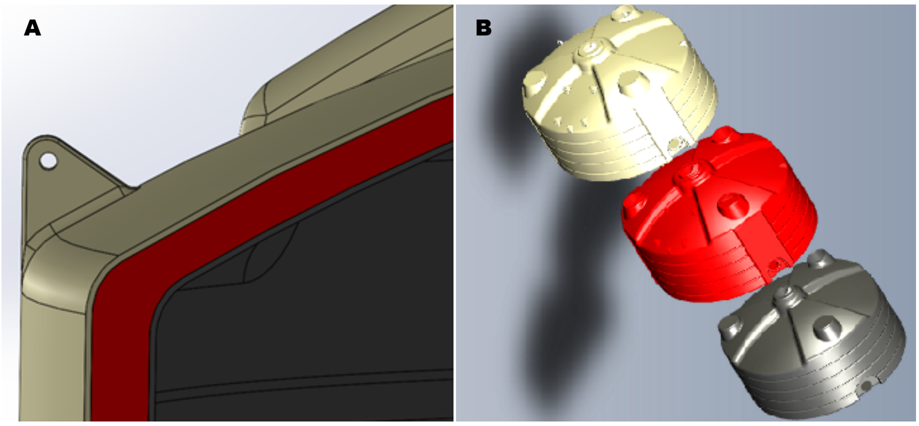

Figure 4: Jacketed-tank structure. (A) Detail of the jacketed-tank structure showing the 10 cm polyurethane thermal insulating layer (in red), and the outer (beige) and inner (carbon black) HDPE walls. (B) Blown-up image of the jacketed tank showing the three layer tank structure.

ton, meaning it can be easily deployed on site with a small munck, and four tanks can be transported at once in a 6x2 truck. Once deployed in position, directly on compact, leveled soil, the remaining installation work consists essentially in connecting the PMTs and the unit electronics and DAQ to the pre-installed cabling, at the assigned positions in the rotomolded structure. A single $15\,\mathrm{m}^3$ water truck is enough to fill a Mercedes tank.

Three trained workers can complete deployment and instrument a tank in 2 hours. Considering that it takes 1 hour to fill a unit with water we estimate that a fully instrumented tank can be deploy in 3 hours. This means that a modest team of 14 workers (including drivers), working on 6 hour shifts, can install and deploy 8 tanks a day, or about 2,000 tanks a year, implying full SWGO deployment in 2.5 years. The simplicity of the deployment and installation process means that work can be carried out on site even in non-ideal environmental conditions, avoiding delays.

6. Conclusion

The Mercedes WCD concept presented was developed for SWGO to minimise the station production and maintenance costs, allowing for easy deployment and flexible optimisation to the various regions and energy ranges to be covered by the array. It is well-suited for a staged observatory construction, following scientifically motivated phases planned to match the available funding.

The successful use of rotomolded tanks as WCD units was demonstrated by the Pierre Auger Observatory over 20 years of field operations. The design presented for SWGO is a highly-innovative – albeit very reliable and and based on proven technology – option for implementation of the Observatory, tailor-made to respond to all of SWGO's specific needs and requirements. We are currently working towards the construction of the first prototype Mercedes tank, to be delivered on site for tests and technology demonstration by the end of the 2023.

Despite our focus on shallow units, rotomolded tanks are also a suitable option for the larger units under consideration in SWGO, and a large prototype tank ($25\,m^3$) is already installed at CBPF, in Rio de Janeiro, as part of an hodoscope for calibration and integration tests for the project.

7. Acknowledgements

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