An Overview of The VERITAS Prototype Telescope And Camera

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Abstract. VERITAS (the Very Energetic Radiation Imaging Telescope Array System) is the next generation ground-based gamma-ray observatory that is being built in southern Arizona by a collaboration of ten institutions in Canada, Ireland, the U.K. and the U.S.A. VERITAS is designed to operate in the range from 50 GeV to 50 TeV with optimal sensitivity near 200 GeV; it will effectively overlap with the next generation of space-based gamma-ray telescopes. The first phase of VERITAS, consisting of four telescopes of 12 m aperture, will be operational by the time of the GLAST launch in 2007. Eventually the array will be expanded to include the full array of seven telescopes on a filled hexagonal grid of side 80 m. A prototype VERITAS telescope with a reduced number of mirrors and signal channels has been built. Its design and performance is described here. The prototype is scheduled to be upgraded to a full 499 pixel camera with 350 mirrors during the autumn of 2004.

Keywords: VERITAS, IACT, gamma ray astronomy, AGN, Supernova remnants

1. Introduction - Very High Energy γ-ray Astronomy

Very High Energy (VHE) γ-ray astronomy is the study of photons in the 50 GeV to 50 TeV energy range. Such photons are only produced by the most exotic objects in the universe with Active Galactic Nuclei (AGN) and Super-Nova Remnants (SNR) among the source categories detected thus far. Given that VHE γ-rays are at the extreme end of the electromagnetic spectra of these objects, they provide excellent constraints on their emission models. The study of VHE γ-rays may also be used to help determine the source of cosmic rays, measure the density of the extragalactic background infrared (IR) radiation and measure the magnetic fields in the shells and nebulae of SNRs. The effective detection of VHE photons is impractical with space-based telescopes due to the low flux of photons and the small collection area of such telescopes. Instead, VHE γ-rays may be indirectly quantified by measuring the Extensive Air Shower (EAS) produced when a γ-ray strikes the earth’s atmosphere.

† The VERITAS collaboration consists of universities and institutions from Ireland, UK, US & Canada. See [http://veritas.sao.arizona.edu/VERITAS_members.html](http://veritas.sao.arizona.edu/VERITAS_members.html) for a full listing.

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2. The Imaging Atmospheric Cherenkov Technique

Upon interacting with the earth’s atmosphere VHE $\gamma$-rays produce cascades of charged particles known as extensive air showers (EAS). These may be detected indirectly at ground level by instruments capable of recording the Cherenkov radiation emitted by the relativistic shower constituents. Unfortunately there exists an almost overwhelming background of EAS produced by charged cosmic rays and an extremely efficient background rejection method is required. The Imaging Atmospheric Cherenkov Technique (IACT) (Weekes and Turver, 1977) allows discrimination between cosmic-ray and gamma-ray initiated EAS by recording the images of the Cherenkov light emitted by the EAS as they develop in the atmosphere (Hillas, 1985). Off-line image analysis techniques are employed to exploit the subtle differences in the physics of the hadronic and electromagnetic EAS, resulting in the rejection of over 99.7% of the background. The imaging cameras are made from arrays of Photo-Multiplier Tubes (PMTs) located in the focal planes of large optical reflectors.

3. VERITAS

The Whipple 10m telescope was the first IACT telescope to be operated (Cawley, 1990). It detected its first VHE $\gamma$-ray source, the Crab Nebula, in 1989 (Weekes et al., 1989). Since that time several other collaborations have built IACT telescopes and the catalogue of detected $\gamma$-ray sources has blossomed to nearly 20 objects (Horan and Weekes, 2004). The angular and energy resolution of the Imaging Atmospheric Cherenkov Technique can be improved by utilising an array of such telescopes. This approach will also lower the energy threshold, thus narrowing the energy gap between space-based and ground-based telescopes. The operation of multiple IACT telescopes in stereo mode has been demonstrated by the HEGRA group (Konopelko, 1999).

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) (Weekes et al., 2002) is a next generation IACT telescope array currently being built in Arizona by the VERITAS collaboration. The first stage in building VERITAS was to construct a single prototype telescope (Wakely et al., 2003). This telescope was erected during the summer of 2003 at the basecamp of the Fred Lawrence Whipple Observatory in Arizona. The primary mission of the prototype telescope was to field test the new technologies being employed by VERITAS and to test system integration. The prototype telescope operated from September 2003 until April 2004.
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4. The VERITAS Prototype

4.1. Telescope and Optics

The VERITAS prototype telescope was built using a custom-designed, welded steel, space-frame Optical Support Structure (OSS) mounted on a commercial positioner (Gibbs et al., 2003). The telescope uses the Davies Cotton (Davies and Cotton, 1957) reflector design. This design comprises multiple identical small mirrors arranged such that they mimic a large single reflector. The most significant advantage of this design is that it removes the requirement to build a single large mirror—which would be problematic in terms of cost, weight and gravitational slumping. The Davies Cotton design is cheap, the mirrors light and individually adjustable. If a single mirror is damaged it can be easily replaced. The most significant disadvantage of the Davies Cotton design is that it is not isochronous. This means that a time spread is introduced to the light pulse arrival time at the camera. The VERITAS telescope’s focal length is 12m, making it an f/1 system for a 12m aperture. This is a significant improvement over the Whipple telescope which is f/0.7 as it will reduce the effect of optical aberrations and is required in order to match the angular size of the PMTs (0.15°). It also reduces the light pulse arrival time spread to 4ns.

The total mass of the OSS, mirrors, counterweights and camera is estimated to be 16,000 kg. RPM has provided a positioner, model PG-4003, to meet the requirements of the VERITAS telescope. The positioner has a design azimuth slew speed of 1°/s and a design ele-
vation slew speed of 0.5°/s, although it was being exercised at more conservative speeds while its performance was evaluated.

Figure 2. Left: The VERTIAS Prototype. Right: The Prototype Camera

Although the prototype employed a full sized OSS, it only held 84 mirrors giving a surface area of 34 m². Each full VERITAS telescope will hold 350 mirrors giving a total mirror area of 140 m². The optical qualities of the VERITAS prototype mirrors were tested at the Whipple Observatory basecamp. They were found to exceed design specifications in terms of reflectivity and curvature. Mirror alignment is achieved using a laser based Mirror Alignment System. The Point Spread Function of the prototype telescope, which is a measure of the mirror alignment, was 0.05° which is within design specifications.

4.2. Camera

In order to detect the extremely faint and brief Cherenkov flash, a low noise, high gain photon counting device with a fast (2.5ns) risetime is required. Despite steady advances in the field of solid state detectors, only Photo Multiplier Tubes (PMTs) currently meet these requirements. A VERITAS camera will comprise 499 1 1/8 inch Photonis XP 2970 PMTs. The PMTs are supplemented with a high bandwidth preamplifier integrated into the PMT base. A charge-injection system is also present in the camera for calibration and diagnostic purposes. This system injects pulsed charges into the preamplifier which simulates Cherenkov events. This can be used to test the electronics and data acquisition systems downstream of the PMTs in a controlled manner without activating the PMTs. Current monitoring systems in the camera provide a measurement of the brightness of the field of view in each pixel and may be used to check tracking. Each full VERITAS camera will also contain environmental sensors. The High Voltage (HV) for the
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PMTs is provided by a multichannel modular commercial power supply (CAEN SY1527/A1932). The VERITAS prototype camera consisted of 255 Hamamatsu PMTs in a ‘half-moon’ configuration. Despite the reduced camera size, the VERITAS prototype performed excellently as a full IACT telescope.

5. Trigger and Calibration Systems

VERITAS utilises a flexible three-level trigger system which allows full-array, sub-array and individual telescope operation. Trigger level one consists of individually programmable constant-fraction discriminators (CFDs) which determine whether an individual pixel has triggered. The level two trigger is a topological hardware trigger which can discriminate between compact Cherenkov events and random night-sky or afterpulse-induced events (Bradbury et al., 1999). Trigger levels one and two constitute the telescope-level trigger while the level three system receives inputs from all the telescopes and generates array-level triggers, and event numbers, based on a geometry-adjusted multiplicity condition. The VERITAS prototype has operated with full implementations of the level one and level two triggers for 250 channels but with a simplified level 3 trigger as sophisticated multi-telescope triggering is not yet required.

Calibration systems installed on the VERITAS prototype telescope include a charge injection system and a nitrogen/dye laser flasher. In addition, atmospheric monitoring stations, a mid-infra-red pyrometer system, and CCD sky quality monitoring cameras are under development.

6. Signal Digitisation and Data Acquisition

The signals from each of the PMTs are digitised by a custom-designed 500 MSPS flash-analogue-to-digital converter (FADC) system (Buckley et al., 2003). The prototype telescope has 25 FADC boards, containing 10 channels each, situated in two VME crates. A third VME crate contains GPS clocks and ancillary modules. Each FADC channel has a dynamic range of $\sim 11$ bits and a memory depth of $\sim 8 \mu s$. The FADCs have zero-suppression capabilities so that channels whose signal do not exceed a programmable threshold do not appear in the data stream.

With the FADCs, VERITAS can sample the charge deposited in each pixel every 2ns. This provides a pulse profile for each pixel for each event. As well as improving the signal to noise ratio, eliminating the
need for delay cables and reducing deadtime, the pulse profile may provide a new technique for discriminating against hadronic events using the time evolution of the EAS.

Readout of the FADCs is accomplished using VMIC Pentium crate computers running the Linux operating system. Each crate computer buffers multiple event fragments until an optimal depth has been reached, when they are then transferred via Scalable Coherent Interface to the telescope event-building system. The telescope event-building system consists of a dual-processor Xeon server running Linux and the data acquisition software is implemented in C++. Built telescope events are sent via ethernet to the harvester machine, where they are combined into array events and analysed, and stored locally on disk for redundancy. The DACQ software is controlled from the central Array-Control system via a CORBA interface.

This integrated data acquisition system has been thoroughly tested on the prototype telescope and found to perform reliably. During the prototype telescope evaluation stage 64 samples were read out for every channel with each event, resulting in a data size of $\sim 16.5$ kBytes per event, at a rate of $\sim 30$ Hz. The full VERITAS telescopes will operate...
with a considerably reduced event size due to zero-suppression and a reduced number of FADC samples per event.

7. Early Results

The VERITAS prototype operated from September 2003 until the end of April 2004. While much of this time was spent testing systems and system integration, a significant amount of quality data was taken on the well established TeV source Markarian 421 (Mrk421). During this period, the nearby Whipple 10m telescope observed this BL Lac in a flaring state, allowing a meaningful comparison in gamma-ray rate between the Whipple 10m telescope and the VERITAS prototype. The prototype detected Mrk421 at 20.5\(\sigma\) over 19.2 hours of observations. During the same period, the prototype telescope’s average rate was 0.8 \(\gamma /\text{min}\) and the Whipple 10m observatory’s was 7 \(\gamma /\text{min}\).

![Figure 4. Left: An alpha plot indicating the detection of Mrk421 (Holder, U. Leeds). Right: An impression of the complete VERITAS-4 array at Horseshoe Canyon, Arizona.](image)

8. Schedule

During the summer of 2004, the prototype camera will be completely disassembled and the new Photonis pixels installed. The remainder of the 350 mirrors will be mounted. When these upgrades are completed the prototype will be redesignated Telescope 1 and will operate at the basecamp of the Whipple Observatory for two years. In the interim,
the VERITAS site at Horseshoe Canyon will be prepared and three telescopes identical to Telescope 1 will be constructed. Upon their completion, Telescope 1 will be moved to Horseshoe Canyon, completing the VERITAS-4 array. This is expected to occur before the summer of 2006.

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