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VERITAS: The Very Energetic Radiation Imaging Telescope Array System

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Abstract. The Very Energetic Radiation Imaging Telescope Array System (VERITAS) represents an important step forward in the study of extreme astrophysical processes in the universe. The seven identical telescopes of VERITAS, each of aperture 10 m, will be deployed in a filled hexagonal pattern of side 80 m; each telescope will have a camera consisting of 499 pixels with a field of view of 3.5°.

1 Introduction

1.1 Next Generation Telescopes

Advances made by the present generation of imaging telescopes justify the construction of an array of large imaging telescopes with the following properties:

- *Better Flux Sensitivity*: detection of sources which emit γ-rays at levels of 0.5% of the Crab Nebula flux at energies of 300 GeV in 50 hours of observation.
- *Reduced Energy Threshold*: an effective energy threshold <100 GeV with significant sensitivity at 50 GeV.
- *Improved Energy Resolution*: an RMS spectral resolution of ΔE/E $<$ 0.10 - 0.15 for an individual shower over a broad energy range (E $>$ 300 GeV).
- *Increased Angular Resolution*: <0.05° for individual showers and source location better than 0.005° (> 100 photons).

All of these objectives can be achieved by VERITAS, an array of large imaging telescopes which are improved versions of the existing Whipple 10 m imaging telescope. The seven telescopes in VERITAS will be identical and will be deployed as shown in Figure 1. Six telescopes will be located at the corners of a hexagon of side 80 m and one will be located at the center. The telescopes will each have a camera consisting of 499 pixels with a field of view of 3.5° diameter.

The VERITAS concept was first described in 1985 prior to the definite detection of any TeV sources (Weekes, 1985).

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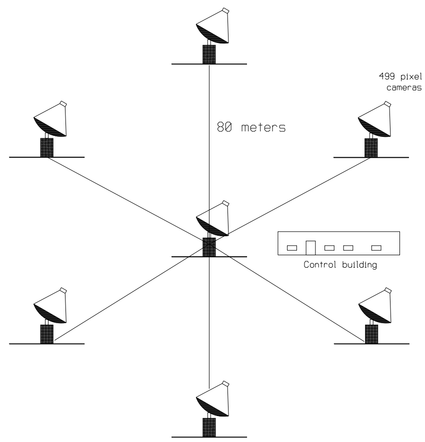

Fig. 1. Layout of telescopes in VERITAS.

2 VERITAS Design

The performance characteristics required of VERITAS are derived from its scientific goals; these and the performance characterisitics have been described in detail elsewhere (Vassiliev, 1999; Weekes et al., 2001).

VERITAS was designed to optimize observations of a variety of sources, each of which may require a different subset of capabilities (e.g., continuous monitoring, large field of view, good flux sensitivity, large collection area, good angular resolution, low energy threshold, accurate energy resolution, prompt response, and broad energy coverage). With these features, VERITAS can observe known and anticipated sources in several observing modes.

In Table 1 the performance characteristics of VERITAS are summarized; these are optimized for point source detection.

Table 1. VERITAS Sensitivity

Characteristic	E	Value
Peak Energy[a]		75 GeV
Flux sensitivity[b]	>100 GeV	$9.1\times10^{-12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
	>300 GeV	$8.0\times10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
	>1 TeV	$1.3\times10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Angular resolution	50 GeV	0.14°
	100 GeV	0.09°
	300 GeV	0.05°
	1 TeV	0.03°
Effective area	50 GeV	$1.0\times10^{3}\mathrm{m}^{2}$
	100 GeV	$1.0\times10^{4}\mathrm{m}^{2}$
	300 GeV	$4.0\times10^{4}\mathrm{m}^{2}$
	1 TeV	$1.0\times10^{5}\mathrm{m}^{2}$
Crab Nebula rates	>100 GeV	50/minute
	>300 GeV	7/minute
	>1 TeV	1/minute
Energy resolution[c]		<15%

[a]Energy at which the rate of photons per unit energy interval from the Crab Nebula is highest for a 4.2 photoelectron trigger threshold.
[b]Minimum integral flux for a 5σ excess (or $\geq$10 events) in 50 hours of observations of a source with a Crab Nebula-like spectrum.
[c]RMS ($\Delta E/E$)

3 Technical Description

3.1 Telescope Design

The Davies-Cotton optical design (Davies and Cotton, 1957) used in the Whipple 10 m reflector (and in many subsequent γ-ray telescopes) has mirror facets which are spherical and identical, facilitating fabrication at a reasonable cost and making alignment easy. This design also has smaller off-axis aberrations than a parabolic reflector so that it has good image quality out to a few degrees from the optic axis. Its one limitation, that the surface is not isochronous, means that the reflector introduces a time-spread into the light pulse. The Davies-Cotton design provides the optimal combination of optical quality and cost effectiveness. Increasing the f-number from f/0.7 to f/1.2 substantially improves the optical quality of the telescope (Figure 2). It is then possible to match the inherent fluctuations in the shower images with a camera that has a reasonable number of pixels ($\approx$ 500) and appropriate FOV ($\approx$3.5°). The larger f/number reduces the time spread to $<$ 4 ns (which is a good match to the inherent width of the shower pulse).

The facets will be made of float glass, ground or slumped, polished, aluminized and anodized. They will be hexagonal in shape to permit closepacking and will be 60 cm across the flats.

3.2 Mounts: Optical Support Structure/Positioner

The VERITAS telescopes will consist of a custom-designed, welded-steel, space-frame Optical Support Structure (OSS) mounted on a commercial positioner. They will have a f/number of 1.2, a rectangular OSS to facilitate the use of mirror covers, and tighter performance specifications than the Whipple 10 m reflector.

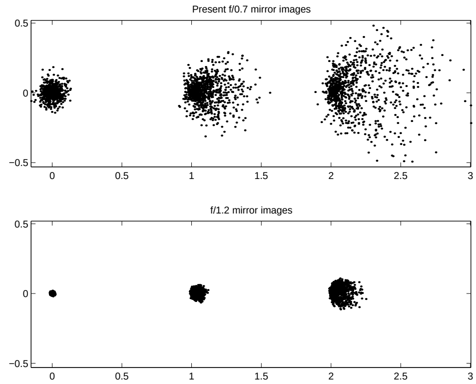

Fig. 2. Point spread images in the focal plane corresponding to a source at 0°, 1°, and 2° off axis for f/numbers of 0.7 (top, Whipple telescope) and 1.2 (bottom, VERITAS). The facet size is 60 cm and the image size is given in degrees.

Cost and performance have been evaluated as the critical parameters of aperture, f-number, wind loading, storm survival, stiffness, and pointing were varied. It was determined that a trussed-steel OSS of 10 x 11 m aperture and 12 m focal length (f/1.2) could be designed to match commercially available positioners (Figure 3). Although initially the OSS will have 250 mirrors (collection area = 75 m^2), it will be capable of supporting 315 mirrors (collection area = 100 m^2).

The telescope RMS blur, RMS decentering, and RMS pointing specifications, with and without corrections (determined by offset-facet alignment and/or lookup tables), are 0.02/0.04 °, 0.01/0.05 °, and 0.02/0.05 °, respectively for wind speeds up to 20 m.p.h. Azimuth slew speed will be 1 °/s and elevation slew speed will be 0.5 °/s. The total weight of the OSS, mirrors, counterweights and the detector is estimated to be 16,000 kg.

When not in use, the mirrors on the reflector will be covered by four "window-blind" covers which will be mounted on the top and bottom of the OSS.

3.3 Electronic Camera

An outline of the major components of the camera is shown in Figure 4 and discussed below.

The array trigger is formed from a combination of individual telescope triggers at the central trigger. The trigger is designed to record all γ-ray events that contain enough light to be usefully identified as γ-ray events (reconstruction threshold) while limiting the trigger rate to a manageable level. When a readout trigger decision has been made for an individual telescope, a sub-array of telescopes or the full array, the control electronics loads the appropriate section of the FADC memory of those signal channels with hits onto a data bus which is read out by the controller and stored in

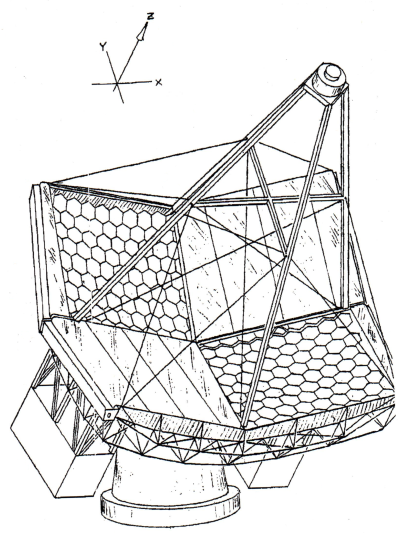

Fig. 3. Engineering sketch of VERITAS telescope based on conceptual design with covers retracted on upper left and lower right quadrants. The telescopes will not initially be populated by mirrors in corners. Sketch by T.Hoffman.

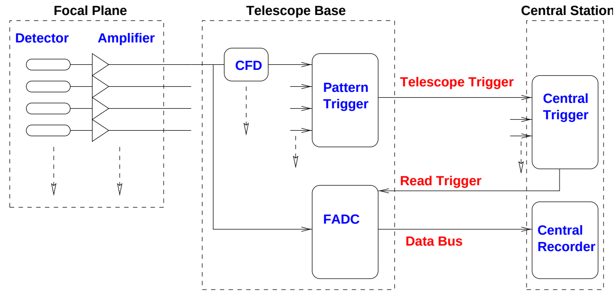

Fig. 4. Outline of electronics. The PMT signals are amplified in the camera head and transmitted to the electronics located in a building near the telescope base. The input analog signals are split with one output fed to fast constant fraction discriminators (CFDs) to form the initial trigger by detecting coincidences on a time-scale from 5 to 15 ns. The outputs from these discriminators are fed to a local pattern trigger unit which tests for adjacent detector hits in the telescope. The other branch of the analog signal from each detector is fed to a flash analog-to-digital converter (FADC) which digitizes the detector waveform into a circulating memory. This results in a digitized version of the signal pulse from each pixel. The telescope trigger signal is sent to the central trigger location where programmable delays are applied to the trigger signal from each telescope to correct for the difference in the time of arrival of the wavefront at the individual telescopes due to the source location in the sky.

reflective memory modules. This information is read out by local CPUs and merged into event data for the telescope. The individual telescope data is transmitted to the central station, merged with data from the other telescopes and stored.

3.3.1 Photomultiplier Tubes:

The low noise, high gain ($> 10^6$), photon counting detector requirements are presently satisfied only by PMTs. The spacing between the centers of the PMTs corresponds to a focal plane angular distance of $0.15°$. The active light collection diameter of the PMTs is 25 mm. The collection efficiency is increased by the use of light concentrators. Tests have identified the Hamamatsu R7065 and the Phillips Photonis XP2900 as PMTs which satisfy the VERITAS requirements.

3.3.2 High Voltage Supply:

Modular commercial high voltage supplies will be used so that each PMT has a separately programmable high voltage. These are used to adjust the PMT gains and to reduce the current draw when a bright star image falls directly on a specific PMT.

3.3.3 Signal Amplifiers:

A custom circuit with a linear amplifier is attached to each PMT in the focus box. The amplifier also provides a secondary input to the data acquisition system which permits charge injection for calibration and diagnostic purposes during daytime.

3.3.4 Cabling:

Pulses are transmitted from the focal plane PMTs to the telescope electronics through 40 m of high quality coaxial cable. This introduces some time dispersion into the signals. An analog optical fiber system with sufficient dynamic range (1:1000) is being tested on the Whipple 10 m telescope (Bond et al., 2001). Fibers introduce no dispersion and are lightweight.

3.3.5 Trigger Electronics

VERITAS must trigger at low PMT threshold levels to achieve its low energy threshold, and with simple trigger schemes this would naturally lead to very high trigger rates. To limit the overall trigger rate and to keep the data acquisition deadtime to an acceptable level, a multi-level trigger scheme has been developed. This system keeps the overall trigger rate below 1 kHz. The four trigger levels are defined as:

Level 1 (CFD). The outputs from the PMTs come directly to constant fraction discriminators (CFDs). The analog bandwidth of this system is $>$ 500 MHz. The discriminator threshold and output pulse width are programmable by command. This module also has a short adjustable delay element to allow the timing in each channel to be matched to better than 2 ns. An analog fanout of the PMT signal is provided from this board to the FADC system. The CFDs constitute the Level 1 trigger. The NSB produces PMT singles rates given by the dotted curve in Figure 11.
Level 2 (PST). A hardware pattern trigger at each telescope based on Level 1 triggers reduces the background by discriminating between photon-initiated shower images, which are compact, and background triggers caused by sky noise or afterpulsing, which have

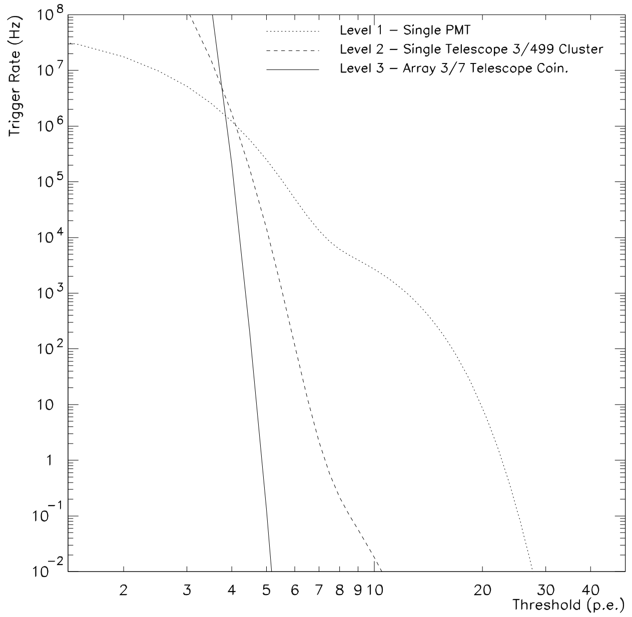

Fig. 5. Expected rates for the various trigger levels of VERITAS as a function of PMT threshold. The various curves are discussed in the text.

random locations in the camera plane. The dashed curve in Figure 11 shows the expected rate of these background events when the coincidence requirement is that at least three nearest neighbors in the 499 pixel camera are hit. The pattern selection trigger (PST) follows the scheme presently being used at the Whipple Telescope (Bradbury et al., 1999).
Level 3 (Array). The central station receives the Level 2 triggers from each telescope. The Level 3 trigger system selectively delays each Level 2 signal to account for the wavefront orientation and determines if the overall array trigger condition is satisfied. The solid curve in Figure 11 shows the expected background rates for this trigger if three of seven telescopes fire within 40 ns coincidence time. If the Level 3 trigger condition is met, readout of the telescope event information is initiated.
Level 4. The background trigger rate can be reduced by demanding that the individual telescope trigger clusters conform to the predicted parallactic displacement of the γ-ray images.

3.3.6 Flash ADCs:

The FADC provides a digitized version of the Cherenkov pulse waveform, giving the maximum information possible about the shape and time structure. These devices allow operation of the individual telescopes well into the NSB, eliminate the need for delay cables (minimizing signal dispersion), and allow real-time calibration of the PMT and signal cable propagation times. Also, the time structure of the pulse is expected to become wider near the edge of the Cherenkov light pool, and with the FADCs these effects can be corrected for in later analysis of the digitized pulses. The increasing availability of high bandwidth FADC chips for commercial purposes makes it possible to include a FADC in every detector channel of VERITAS. Commercial modules are expensive and VERITAS will use custom-built units. A prototype FADC system has been developed and tested on the Whipple telescope and appears to have all the necessary parameters for VERITAS (Buckley et al., 1999). Each FADC channel uses a commercially available 8-bit FADC integrated circuit. This system has a sample rate of 500 MHz, a memory depth of 64 microseconds, and a novel autoranging gain switch that provides a dynamic range of 0 to 1020 p.e. with no loss of small signal bandwidth.

3.3.7 Data Acquisition:

The data acquisition electronics are based largely around the VME standard electronic architecture: a fast VME backplane and distributed computation performed by local CPUs running a real-time operating system. Each controller will be connected, using fast, fiber-optic connections to a local workstation which in turn is connected to a central high speed switch connected to the central CPU. The central CPU will perform control and quicklook functions, further data compression and integration of the distributed data.

3.4 Calibration

The VERITAS calibration system has been designed to provide automated, redundant measurements of all relevant calibration parameters as well as to test system functionality automatically during the daytime. It consists of three different subsystems: optical injection, electronic or charge injection, and atmospheric monitoring.

4 Schedule

A prototype telescope is under construction as an R&D project pending approval of the complete array. It is hoped to have the array on-line in 2005.

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