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VERITAS: Performance characteristics (baseline design).

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Abstract

VERITAS is a proposed major ground-based gamma-ray observatory to be built at the Whipple Observatory in southern Arizona, USA. It will consist of an array of seven 10m imaging Cherenkov telescopes designed to conduct gamma-ray observations in the energy range of 50 GeV - 50 TeV. A description of the baseline VERITAS design and optimization criteria are presented. We provide basic characteristics of the array performance for observations of point sources, such as angular resolution, energy threshold, energy resolution, and integral flux sensitivity. The limiting factors of the VERITAS performance are discussed.

1 Introduction:

Recent discoveries in ground-based Very High Energy (VHE) astronomy (reviewed in Ong 1998) has been achieved due to two major advances in the atmospheric Cherenkov technique; imaging (Hillas 1985, Fegan 1997), and stereoscopy (Aharonian et al. 1997a, 1997b, Krennrich et al. 1995) of the observations of atmospheric cascades. The former, pioneered at the Whipple and Crimean γ-ray observatories, has been adopted now by most existing ground based γ-ray instruments. The latter, demonstrated by the HEGRA collaboration, is now being considered as a prime technique for the next generation of ground-based VHE observatories: VERITAS (Weekes et al. 1999), HESS (Aharonian et al. 1999), and NEW CANGAROO (Tanimori et al. 1999). The scientific goals of these projects are described elsewhere (Weekes et al. 1999), the summary of the physics highlights to be accomplished with VERITAS instrument are presented by Bradbury et al. (1999). In this submission, we summarize the technical characteristics of VERITAS and discuss the major performance parameters of this proposed VHE observatory.

2 Technical characteristics:

The VERITAS design has been optimized for maximum sensitivity to point sources in the energy range 100 GeV - 10 TeV, but with significant sensitivity in the range 50 GeV - 100 GeV and from 10 TeV to 50 TeV. Optimization has been performed with fixed total number of channels which determines the cost of the project. The suggested layout of the array is shown in Figure 1, and its specifications are provided in Table 1. Brief arguments for the baseline configuration can be found in Vassiliev et al. (1999), while design simulations of VERITAS are described in Weekes et al. (1999). The underlying motivations for the array design were derived from the physics goals of the project to create an instrument sensitive to $\sim$ 100 GeV photons with high angular and energy resolutions, but also versatile enough to accomplish a variety of astronomical tasks: point source observations with a low energy threshold, observation of extended sources, sky surveys, and simultaneous monitoring of several objects. Some of the physics goals would require a different, sometimes incompatible, optimum VERITAS design. For example,

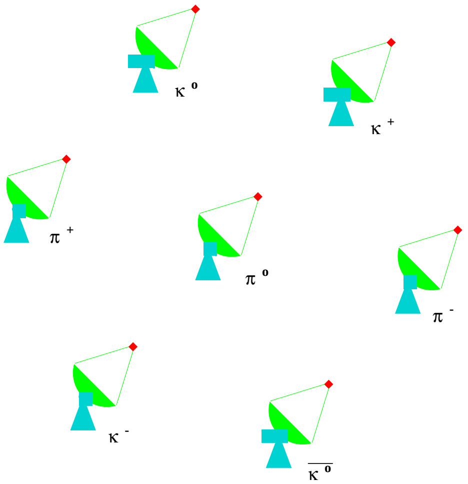

Figure 1: VERITAS hexagonal layout

Table 1: Specifications of the baseline VERITAS design.

Location	Montosa Canyon, Arizona, USA
Array elevation	1390 m a.s.l.
Number of telescopes	7 (hexagonal layout)
Telescope spacing	80 m
Mirror	Davies-Cotton
Reflector aperture/area	10 m / 78.6 m^2
Focal length	12 m
Facets	244, 61 cm hexagon
Camera	Homogeneous
Field of View	3.5 deg
Number of pixels	499
Pixel Spacing	0.148 deg

detection of high energy photons ($10 - 50$ TeV) and observation of objects with large angular extent ($> 1^\circ$) generally require a larger field of view for the instrument. VERITAS will accomplish such tasks by observation of astrophysical objects at large zenith angles and by different array operation modes, e.g., offset pointing of individual telescopes to cover an extended object. At the same time the small, 0.15°, pixel size of the telescope cameras provides a substantial sensitivity to photons with energies below 75 GeV, the expected energy threshold of VERITAS for point source observations. Approximately 20% of the photons, which are detected and successfully reconstructed, will have energies lower than 75 GeV extending the sensitive energy range of VERITAS to at least 50 GeV.

3 Performance characteristics:

The energy threshold of VERITAS is limited by fluctuations of the Night Sky Background (NSB). To suppress spurious accidental signals, a pattern trigger has been developed and tested (Bradbury et al. 1999). To operate telescopes at the highest rate and minimum energy threshold, a 500 MHz flash ADC system will be used (Buckley et al. 1999) which virtually eliminates the dead time of the array. Utilizing these technologies, we expect that VERITAS will be able to operate at a threshold of $4 - 7$ photoelectrons (pe) per pixel requiring coincidence between 2,3 telescopes of the array within 40 nsec, and coincidence between 2,3 adjacent pixels of the cameras within 15 nsec. Depending on the brightness of the different regions of the sky we expect to achieve an energy threshold of $70 - 100$ GeV for point source observations with maximum sensitivity. The energy threshold, E_t, of VERITAS is defined here as the photon energy at which the differential detection rate of the photons (retained for analysis after all selection cuts) from a source with spectrum $\propto E^{-2.5}$ is maximal. Thus, the array energy threshold is directly related to an array trigger threshold defined by a hardware or software cut on the number of photoelectrons in the second or third adjacent pixel of the shower image.

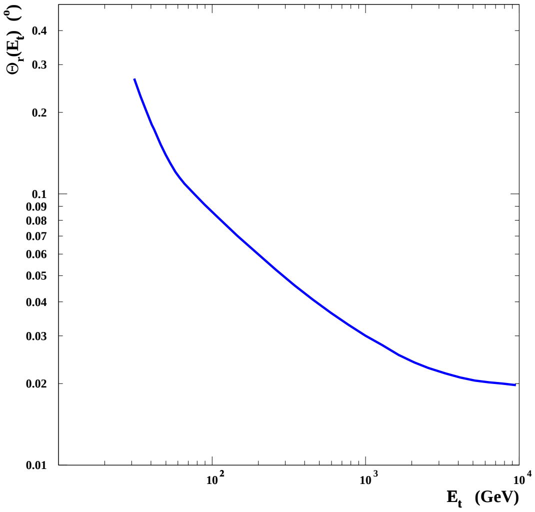

Figure 2: Angular resolution of VERITAS for a single photon as a function of array energy threshold. Selection criteria for photons correspond to VERITAS operation with maximum sensitivity to a point source.

When the array operates at the lowest energy threshold, requiring a trigger of 3 adjacent pixels and 3 out of 7 telescopes, the collection area of VERITAS will be $1.1 - 7.4 \times 10^4 \mathrm{m}^2$ for 100 GeV, $10 - 25 \times 10^4 \mathrm{m}^2$ for 1 TeV, and $13 - 34 \times 10^4 \mathrm{m}^2$ for 10 TeV. The upper bounds correspond to all photons from the point source which trigger the array and whose arrival direction is reconstructed within the camera field of view. The lower bounds correspond to photons which satisfy strict reconstruction criteria which effectively remove the cosmic-ray background allowing observations with maximum sensitivity. The high angular resolution of the array (shown in Fig. 2) is one of the most important characteristics which determines the sensitivity of VERITAS to point sources. We expect that VERITAS will have better angular resolution than any existing detector operating above a few MeV. The excellent angular resolution of the array is due to stereoscopic imaging. For a single telescope, the photon arrival direction is better defined in the direction perpendicular to the main axis of the image. The parallel direction is reasonably constrained by image ellipticity (Buckley et al. 1998). Multiple sampling of the shower from several telescopes allows precise reconstruction of the photon origin in both directions. This feature of the array will also be critical for mapping the emission regions of extended sources with accuracy close to one arcminute.

The performance of VERITAS is summarized by its flux sensitivity. The minimum detectable flux of γ-rays is defined by the confidence level required for detection or the statistics of the detected photons. We require a 5σ excess of γ-rays above the background, or 10 photons (below this, Poisson statistics must be used to derive the confidence level). We estimate the flux sensitivity for 50 hours of observations on an object with a spectrum $\propto E^{-2.5}$, which is close to the Crab Nebula spectrum seen in this energy range.

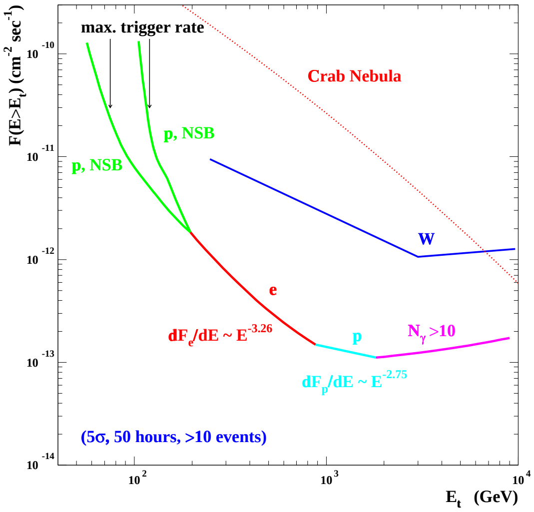

Figure 3: The sensitivity of VERITAS to point-like sources in 50 hours of observing. The dominant background as a function of energy threshold is indicated (see text for details). The two curves at low energies indicate the sensitivity of VERITAS in dark (lower curve) and bright (upper curve) NSB regions. The integral flux from the Crab Nebulae (Hillas et al. 1998) and estimated sensitivity of the Whipple telescope are given for comparison.

The γ-ray flux sensitivity of VERITAS for point sources as a function of array energy threshold is shown in Figure 3. The complex shape of the sensitivity curve is caused by different energy regions being dominated by the different backgrounds as indicated in the figure. For energies above 2 – 3 TeV, the sensitivity of VERITAS is limited by photon statistics. Larger telescope fields of view can improve this sensitivity in the future, as can large zenith angle observations. In the region near 1 TeV, the sensitivity is limited by rare cosmic-ray protons which mimic γ-rays by converting most of their energy into an electromagnetic cascade in the first few interactions. A chain of very rare coincidences must occur for such events to pass all selection criteria: almost all of the proton's energy must be transferred to an electromagnetic cascade leaving no hadronic shower core; the transverse momentum distribution of secondary photons must be very narrow to generate a compact cascade; the axis of the shower must be precisely aligned with the telescope axis; and the impact parameter of such a shower cannot be large if it is to produce a well-defined image. The rate of such events is not known exactly due to large variations in MC predictions caused by uncertainties in the different hadronic interaction models used. Therefore, we show the estimated rate of such events. In the energy region between 200 GeV and $\sim$1 TeV, the background rejection of VERITAS is so good that diffuse cosmic-ray electrons are the dominant background instead of hadronic cosmic rays. The diffuse electron spectrum is very steep, so the decrease in the sensitivity of VERITAS with decreasing energy is more rapid in this region. Because electrons and γ-rays produce nearly identical electromagnetic cascades in the atmosphere, the only way to reduce this background is with improved angular resolution algorithms. Increasing the quantum efficiency of the photodetectors and decreasing the pixel size in future VERITAS upgrades will also improve array performance in this region. The region below 200 GeV is limited by the NSB and cosmic-ray protons. At this level, the amount of collected Cherenkov light is so small that shower images have very few pixels which pass the image cleaning process. As such, small fluctuations in the NSB significantly affect the reconstruction of both γ-rays and protons. Thus, the amount of NSB light determines the sensitivity of VERITAS in this region (and thereby the energy threshold). The more sensitive of the two curves indicates a relatively dark observation region (like an AGN with no bright stars in the FoV) while the less sensitive curve indicates a region where the NSB light is approximately 4 times brighter (like in some regions of the Galactic plane). The arrows show the lowest energy threshold at which VERITAS will be able to operate, limited by the higher than 1 MHz accidental trigger rates of single telescopes caused by the NSB. We anticipate a counting rate of $20-40$ well reconstructed photons per minute from the Crab Nebula for VERITAS observations close to these limits.

The energy resolution of VERITAS will be considerably better than that of the Whipple Observatory telescope for three reasons: (1) the shower core location will be known with an accuracy of about 10 m, (2) several telescopes will view each event at different distances from the shower core, and (3) each camera will have finer pixellation (0.15° vs. 0.25°). For the Whipple telescope, the RMS energy resolution using the technique described in Mohanty et al. (1998) gives $\Delta E/E \approx 0.35$. We adopted this method for stereoscopic observations, as explained in Weekes et al. (1999), and obtained the energy resolution shown in Figure 4. For our estimates, we used simulated showers from γ-rays with energies > 100 GeV whose size was above 10 pe per image, core location was in the range $65-180$ m from telescope, the position of the image centroid was in the interval $0.5-1.4°$, and whose arrival direction was reconstructed to within $0.1°$ of the source position. The resolution improves slowly as the energy of the shower increases. For low energy events (~ 100 GeV) the resolution will likely be improved through more sophisticated energy estimates and through the use of more restrictive cuts on events used in the energy analysis. The improved energy resolution of VERITAS will help resolve spectral features, such as a possible neutralino annihilation line from the Galactic center or spectral cut-offs in AGN, and permit better estimation of characteristics of the emission regions in sources, such as the magnetic field in the vicinity of SNRs and AGN.

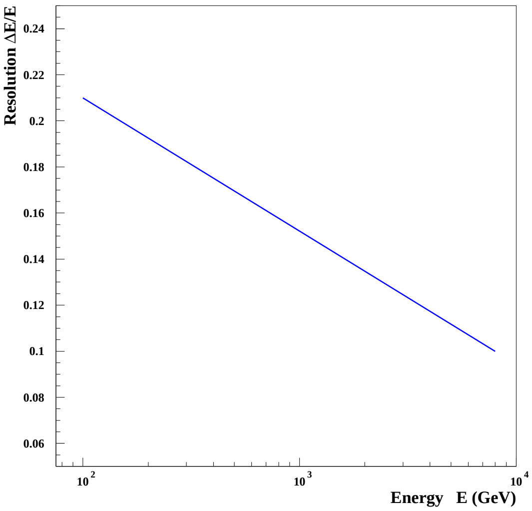

Figure 4: Estimate of VERITAS energy resolution

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