

Deployment of the VERITAS observatory

S. LeBohec^b, R.W. Atkins^b, H. M. Badran^a, G. Blaylock^c, I.H. Bond^d, P.J. Boyle^e, S.M. Bradbury^d, J.H. Buckley^f, D.A. Carter-Lewis^g, O. Celik^h, Y.C.K. Chow^h, P. Coganⁱ, W. Cui^j, M.K. Danielⁱ, I. de la Calle Perez^k, C. Dowdall^{a, i}, P. Dowkontt^f, C. Duke^l, T. Ergin^f, A.D. Falcone^m, D.J. Feganⁱ, S.J. Fegan^h, J.P. Finley^j, P. Fortin^t, L. Fortsonⁿ, S. Gammellⁱ, K. Gibbs^a, G.H. Gillanders^o, J. Grube^d, J. Hall^b, D. Hanna^p, E. Hays^e, J. Holder^b, D. Horan^a, S.B. Hughes^f, T.B. Humensky^e, P. Kaaret^q, G.E. Kenny^o, M. Kertzmann^r, D. Kieda^b, J. Kildea^p, J. Knapp^d, K. Kosack^f, H. Krawczynski^f, F. Krennrich^g, M.J. Lang^o, E. Linton^e, J. Lloyd-Evans^d, G. Maier^d, H. Manseri^b, A. Milovanovic^d, P. Moriarty^s, R. Mukherjee^t, T.N. Nagai^b, P.A. Ogden^d, M. Olevitch^f, R.A. Ong^h, J.S. Perkins^f, D. Petry^u, F. Pizlo^j, M. Pohl^g, B. Power-Mooneyⁱ, J. Quinnⁱ, M. Quinn^o, K. Ragan^p, P.T. Reynolds, P. Rebillot, H.J. Rose, M. Schroedter, G.H. Sembroski, D. Steeleⁿ, S.P. Swordy^e, A. Syson^d, L. Valcarcel^p, V.V. Vassiliev^h, R.G. Wagner^x, S.P. Wakely^e, G. Walker^b, T.C. Weekes^a, R.J. White^d, D.A. Williams^w, J. Zweerink^h

^a Harvard-Smithsonian Center for Astrophysics, Amado, AZ 85645-0097 USA;

^b Physics Dept., University of Utah, Salt Lake City, UT 84112 USA;

^c Dept. of Physics, University of Massachusetts, Amherst, MA, 01003-4525;

^d School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK;

^e Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA;

^f Dept. of Physics, Washington University, St. Louis, MO 63130, USA;

^g Dept. of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA;

^h Dept. of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA;

ⁱ Physics Dept., National University of Ireland, Dublin, Ireland;

^j Dept. of Physics, Purdue University, West Lafayette, IN 47907, USA;

^k Dept. of Physics, Grinnell College, Grinnell, IA 50112-1690, USA;

^l Dept. of Physics, University of Oxford, Oxford, OX1 3RH, UK;

^m Dept. of Astronomy, Penn State University, University Park, PA 16802, USA;

ⁿ Adler Planetarium, Chicago, IL 60605;

^o Physics Dept., National University of Ireland, Galway;

^p Physics Dept., McGill University, Montreal, QC H3A 2T8, Canada;

^q Dept. of Physics and Astronomy, Van Allen Hall, Iowa City, IA 52242, USA;

^r Dept. of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA;

^s Galway-Mayo Institute of Technology, Dublin Road, Galway, Ireland;

^t Dept. of Physics and Astronomy, Barnard College, Columbia University, NY 10027 USA;

^u N.A.S.A./Goddard Space-Flight Center, Code 6, Greenbelt, MD USA;

^v Cork Institute of Technology, Bishopstown, Cork, Ireland;

^w Dept. of Physics, University of California, Santa Cruz, CA 95064, USA;

^x Argonne National Lab., Illinois, USA

E-mail: lebohec@physics.utah.edu

Abstract. The Very Energetic Radiation Imaging Telescope Array System (VERITAS) being constructed in Southern Arizona consists of an array of four Atmospheric Cherenkov 12 m Telescopes designed to observe astrophysical gamma rays in the energy range from 100 GeV to tens of TeV. A first telescope has been in operation on a temporary site since the end of 2004 and meets all specifications. The second is being installed on the same site, 85 m from the first, in order to test stereoscopic capabilities. The full system of four telescopes is expected to be installed on the definitive site by the end of 2006.

1. Introduction

The Imaging Atmospheric Cherenkov Technique (IACT) was developed in large part around the Fred Lawrence Whipple Observatory (FLWO) 10m telescope. The detection of TeV gamma radiation from the Crab Nebula in 1989 [?] validated the technique which was soon recognized as offering the greatest potential in terms of both background discrimination and low threshold capability in the very high energy gamma-ray regime. The idea of observing atmospheric showers stereoscopically from two or more telescopes was explored at the FLWO [?] but the power of this addition to the IACT was only fully revealed by the HEGRA experiment [?] which consisted of an array of 5 telescopes of modest size offering a threshold of ~ 700 GeV. Very High Energy gamma ray experiments of the present generation essentially result from the idea of combining several large IACT telescopes in a stereoscopic array.

The original concept of VERITAS, with 9 telescopes, was proposed in 1996 approximately at the same time as other projects abroad. Since then, the CANGAROO collaboration has developed an array of four 10 m telescopes in southern Australia [?], the H.E.S.S. collaboration has installed a four 12 m telescope array in Namibia [?] and the MAGIC collaboration has constructed a 17 m telescope [?] which will soon be completed by a second 85 m away for stereoscopic observations. The benefit from stereoscopy is two fold: it improves the accuracy of event reconstruction and it allows discrimination against muon arc events, the dominant irreducible background below 300 GeV for individual telescopes, that prevented earlier experiment from reaching energies below 300 GeV with sufficient sensitivity. The experiment that has had the greatest success is H.E.S.S., which has already been able to increase the catalog of TeV emitters by more than 20 objects [?, ?], including various potential cosmic ray accelerators among which are Super-Nova Remnants, Pulsar Wind Nebulae, one micro-quasar, one binary pulsar, Active Galactic Nuclei and a handful of still not clearly identified objects which in many cases coincide with objects in the EGRET catalog [?].

This explosion of discoveries places the Atmospheric Cherenkov Technique on the same footing with other wave band domains for the observation of the non-thermal universe. Unfortunately the VERITAS project, of a design very similar to that of H.E.S.S., has been slowed down by funding and site access difficulties. At the end of 2003, the project was finally approved and funded at the level of four telescopes, to be installed in the Horseshoe Canyon on Kitt Peak. A first phase consisted of the construction of a prototype telescope at the base camp of the FLWO with a third of the mirror area and half of the electronics in 2003. In 2004, while the Horseshoe Canyon site infrastructure was being developed, the prototype was upgraded to become the first VERITAS telescope, which has been in operation since early 2005. In spring 2005, it was decided to install a second telescope at the FLWO site while continuing the construction of telescopes 3 and 4. This is now (October 2005) in progress (see figure ??) and stereoscopic observations are expected to start in December 2005 for a full test of the system and astrophysical observations during spring 2006. We still hope to be able

to have the entire array of four telescopes installed in the Horseshoe Canyon by the end of 2006. In this paper we will give a brief technical description of the VERITAS array, present the performance of telescope 1 and conclude with the expected performance of the complete array, while reviewing the science potential of the VERITAS observatory in the light of the recent discoveries by our colleagues in the Southern Hemisphere.

2. The VERITAS array

The four VERITAS telescopes are identical and they will be arranged in a centered equilateral triangle pattern, 80 m in radius.

Each telescope is a 350 mirror facet 12 m collector ($\sim 110 \text{ m}^2$) of Davies-Cotton design with a focal length of 12 m. The Davies-Cotton design minimizes the effects of aberrations at large angle for larger aperture systems. The point spread function was measured to be 0.06° . Telescope 1 demonstrated the capability of tracking with a relative accuracy of better than 0.01° and a slew rate of 1° s^{-1} .

The camera consists of 499 photo-multiplier tubes (PMTs) arranged in a hexagonal lattice with 0.15° angular spacing covering a total field of view of 3.5° . A plate of light collecting cones is being designed to be placed in front of the PMT matrix in order to minimize dead space and alleviate the effects of stray light not coming from the mirror. The PMTs are operated at a gain of 2×10^5 and their signals are amplified by an amplifier integrated in the base mount which also allows for the measurement of the anode current and the injection of pulses for system tests in the day time.

The PMT signals are sent via ~ 50 m of cable to the electronics system in the counting house. The signals are digitized in 8 bits at a rate of 500 MHz [?]. In order to improve the dynamic range, an analog switch sends the signal to the FADC via a lower gain and extra delay circuit whenever the amplitude exceeds the high gain dynamic range. For each event, 24 samples (48 ns) from each of the 500 channels are recorded in the data, enabling analysis of the time structure of the images [?] as shown in figure ???. This makes the event size 13.5 kb and brings the dead time to 8 % at the nominal single telescope trigger rate of 150 Hz. In order to allow for higher data rate, it is possible to record only those channels for which the pulse charge exceeds a programmable value.

The trigger decision results from three levels in the electronics. Each channel is equipped with a constant fraction discriminator (CFD) at the 6-7 photo-electron level in our one telescope test. Within each camera the CFD outputs are collected by a pattern sensitive coincidence [?] system programmed to detect any coincidence of three neighbouring pixels. Individual telescope triggers are then collected via optical fibers in the central control building where they are delayed and combined to form the array trigger. The array trigger is dispatched to the whole array to request the data read out. This array trigger system will be tested at the end of 2005 when telescope 2 will be operational. Figure ?? gives an outline of the electronics.

3. Performance of telescope 1

The critical test of telescope 1 was the observation of the Crab Nebula. Figure ?? shows the result of the standard analysis applied to 3.9 hours of data obtained in the direction of the Crab Nebula and resulting in a detection with a significance of ~ 20 standard deviations above background [?]. This is close to a factor of two improvement in sensitivity in comparison to the Whipple 10m telescope. It should be noted that this improvement is obtained without the focal plane light collecting cones. Furthermore, moving the telescope to the Horseshoe Canyon at higher altitude is expected to reduce the threshold and improve the sensitivity. More importantly, in order to eliminate muons arcs that constitute an irreducible background in the 100 GeV-200 GeV range, the threshold is artificially increased in the analysis. In stereoscopic observations this will no longer be necessary as the image analysis will reject all muon events on the basis of geometrical considerations.

The detection of the TeV emission from the Crab Nebula also offers the opportunity to test our understanding of the telescope response to gamma rays. The VERITAS telescope 1 was modeled in detail using the GrISU [?] simulation program. Tests of simulations were obtained from studying muon ring images [?] as well as side-on views of a laser [?] shot at zenith. This combined with the measurement of single photo-electrons [?] allowed to precisely fix the overall efficiency and gain of the system. The Crab Nebula result can then be compared to predictions based on simulations [?]. The observed gamma-ray event rate passing the standard analysis is 2.2 min^{-1} which compares well with the predicted rate of $(2.1 \pm 0.1) \text{ min}^{-1}$. Also the distributions of all standard event parameters in the real data are very well reproduced by simulations. Even the background event rate of 150 Hz is in perfect agreement with simulations. The single telescope analysis threshold (defined as the energy for which the Crab Nebula gamma ray rate per energy interval peaks) is 360 GeV and the trigger level threshold is 150 GeV.

4. Prospects for VERITAS

The performance of VERITAS telescope 1 and its compatibility with simulation studies gives further confidence in the predicted sensitivity that VERITAS should achieve [?]. The 5 standard deviations point source sensitivity above 100 GeV should reach 1.5 mCrab in 50 hours of observation with the full four telescope system. In comparison to individual IACT telescopes, this typically corresponds to more than one order of magnitude improvement in sensitivity at a few hundred GeV and opens new ground for a scientific program in which telescope time will be shared between extragalactic and galactic objects.

The present catalog of extragalactic sources counts 11 objects [?], 10 of them being identified as BL-Lac or blazars in which the jet is pointed along the line of sight. Within this catalog, only 3 objects have been detected with high enough significance and over a

long enough period of time for detailed spectral, variability and multi-wavelength studies to have been possible. These studies revealed complex behavior (see for example [?] and [?]) and are a call for using the newly acquired sensitivity to extend the BL-Lac catalog and study the known objects in more detail. The three most recent additions to the catalog are due to H.E.S.S. [?, ?] and MAGIC [?] and have redshifts from 0.165 to 0.186 suggesting absorption effects in the Extragalactic Background Light to be less important than previously expected. This too makes contribution to the growth of the extragalactic catalog a major goal for VERITAS. The one non-BL-Lac object in the extragalactic catalog of TeV emitters is M87, a radio galaxy. VERITAS will be used for detailed spectral and variability study of this object as well as other, non-blazar extragalactic objects like star-burst galaxies and galaxy clusters.

The Galactic program is more exploratory and will be centered on galactic scan programs, a strategy which has turned out to be extremely fruitful for H.E.S.S. [?] in the Southern Hemisphere. There is no reason to anticipate the Northern Hemisphere should be less rewarding to VERITAS than the southern has been for H.E.S.S.. A region of particular interest is the Cygnus arm region where an unidentified TeV emitter (TeV2032) detected with HEGRA [?] is located. It is also the region where the diffuse galactic emission reported by MILAGRO [?] reaches its maximum. Observations of specific Super Nova Remnants, molecular clouds and compact objects like micro-quasars and binary pulsars will also take up important fractions of the observing programs. These searches will also be guided in part by space based observations.

The scientific program of VERITAS will start in spring 2006 with the two telescopes in place at the FLWO. As first results will be coming up, the VERITAS array will be installed on its definitive site and directions for the future development of the fast growing field of very high energy gamma ray astronomy should be identified.

Acknowledgment: This research is supported by grants from the U.S. Department of Energy, the National Science Foundation, the Smithsonian Institution, by NSERC in Canada, by Science Foundation in Ireland and by PPARC in the UK.

References

- [1] F., A., Aharonian et al., 2005, Science, 307,1938
- [2] F., A., Aharonian et al., 2002, Astron.Astrophys., 393, L37
- [3] M., Blazejowski et al., 2005, ApJ in press, (astro-ph/0505325)
- [4] S., M., Bradbury & H., J., Rose, Nucl. Instr. Meth. A, 481,521
- [5] J., H., Buckley et al., 2003, 28th ICRC, Tsukuba, Japan
- [6] C., Duke & S.LeBohec, <http://www.physics.utah.edu/gammaray/GrISU/>
- [7] R., C., Hartman et al., 1999m ApJS, 123,79
- [8] J., A., Hinton et al., 2004, New Astron. Rev., 48, 331
- [9] J., Holder et al., 2005, Proc. 29th ICRC, Pune, India
- [10] J., Holder et al., 2005, Proc. 29th ICRC, Pune, India
- [11] T., B., Humensky et al., 2005, Proc. 29th ICRC, Pune, India
- [12] A., Kohmle et al., 1996, Astropart. Phys., 5, 119
- [13] F., Krennrich et al., 2002, ApJL, 575, L9
- [14] F., Krennrich et al., 1998, Astropart. Phys., 8, 213

- [15] H., Kubo et al., 2004, *New Astron. Rev.*, 48,323
- [16] E., Lorenz, 2004, *New Astron. Rev.*, 48, 339
- [17] G., Maier et al, 2005, *Proc. 29th ICRC*, Pune, India
- [18] M., Meyer et al, 2005, *Proc. 29th ICRC*, Pune, India
- [19] R., A., Ong, 2005, OG1 Rapporteur, *Proc. 29th ICRC*, Pune, India
- [20] S., Pita et al., 2005, *Proc. 29th ICRC*, Pune, India
- [21] G., Rowell, 2005, these proceedings
- [22] N., Shepherd et al., 2005, *Proc. 29th ICRC*, Pune, India
- [23] A., J., Smith et al., 2005, *Proc. 29th ICRC*, Pune, India
- [24] M., Tluczykont et al., 2005, *Proc. 29th ICRC*, Pune, India
- [25] T.C. Weekes et al., 2002, *Astropart. Phys.*, 17,221
- [26] T.C. Weekes et al., 1989, *ApJ*, 342,379

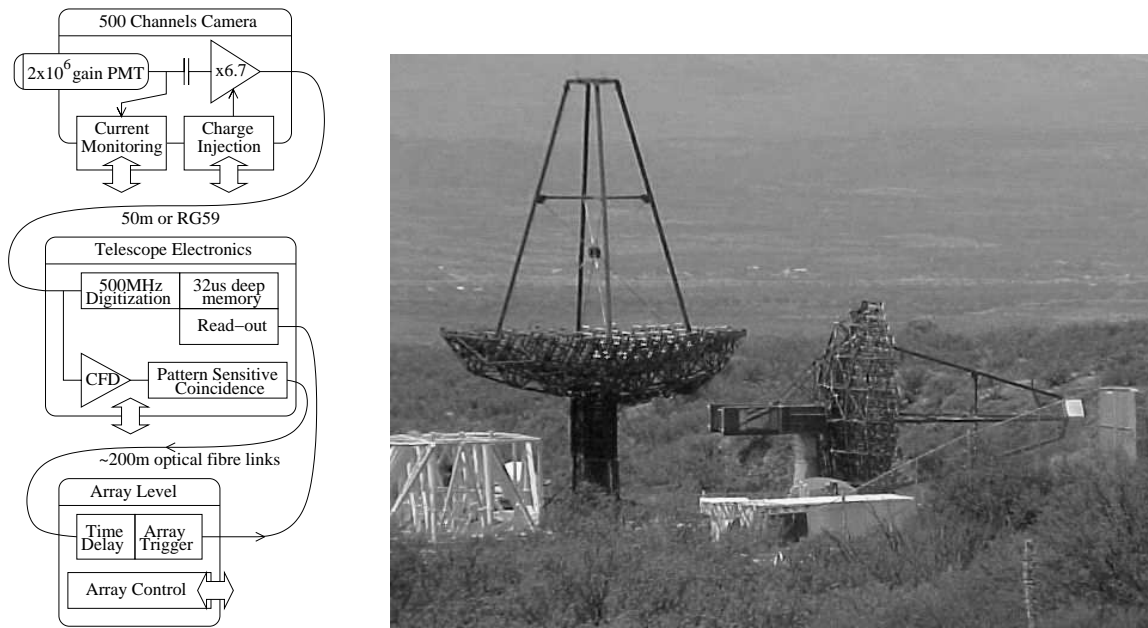


Figure 1. Left: Outline of the VERITAS electronic system. **Right:** The two VERITAS telescopes at the FLWO base-camp.

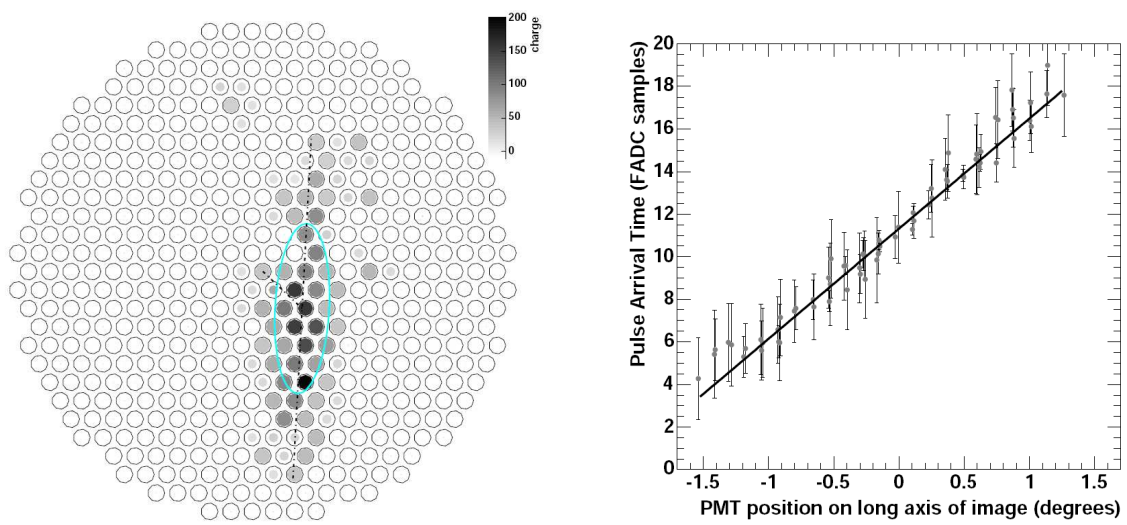


Figure 2. Left: Cosmic ray shower image recorded with VERITAS telescope 1 **Right:** Pulse arrival times (1 FADC sample = 2 ns) as a function of the pixel position along the major axis of the image.

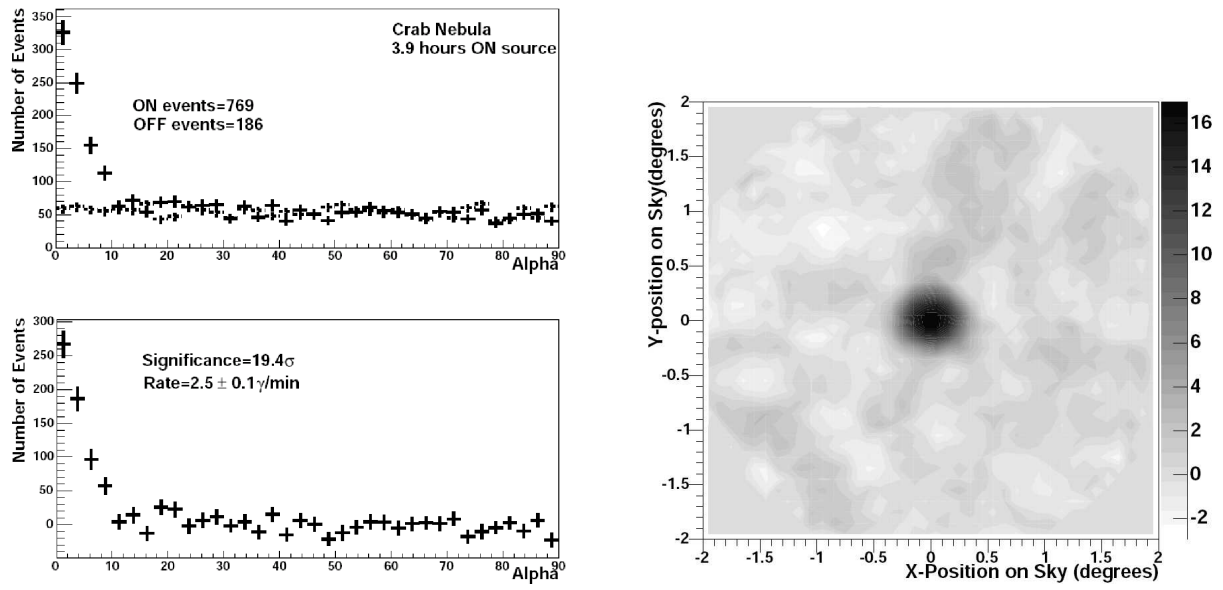


Figure 3. Left: So called α -plot showing the distribution of the angle between the image major axis and the line from the image center to the source position for ON, OFF (top) and ON-OFF (bottom) data after gamma-ray selection cuts are applied. **Right:** Two dimensional significance map of event by event reconstructed source position.