The VERITAS Survey of the Cygnus Region of the Galactic Plane

Amanda Weinstein*, **for the VERITAS Collaboration†**

* *University of California Los Angeles, 475 Portola Plaza, Los Angeles, CA 90095 USA*
† *see R. A. Ong et al. (these proceedings) or http://veritas.sao.arizona.edu/conferences/authors?icrc2009*

***Abstract*. The Cygnus region of the Galactic plane contains many known supernova remnants, pulsars, X-ray and GeV gamma-ray emitters which make it a prime candidate for a Very High Energy (VHE) gamma-ray survey in the Northern Hemisphere. The VERITAS observatory, an array of four atmospheric Cherenkov telescopes located at the base of Mt. Hopkins in southern Arizona, USA, has carried out an extensive survey of the Cygnus region between 67 and 82 degrees in galactic longitude and between -1 and 4 degrees in galactic latitude. The survey, comprising more than 140 hours of observations, reaches an average VHE flux sensitivity of better than 4% of the Crab Nebula at energies above 200 GeV. Here we report on the preliminary results from this survey.**

***Keywords*: gamma rays, galactic observations**

I. Introduction

To date, only a few moderate-scale surveys have been performed in gamma rays between 100 GeV and 10 TeV: the HESS scan of the central region of the Galactic Plane[1], the much less sensitive HEGRA survey of the quarter of the Galactic Plane between $-2°$ and $85°$ in galactic longitude[2], and the VERITAS scan of the Cygnus region under discussion here. However, there is a strong motivation for performing such surveys; an unbiased search of a substantial region of sky is less subject to the experimental and theoretical prejudices that guide most VHE gamma-ray observations, and therefore (as demonstrated by HESS) offers greater scope for serendipitous discoveries. An unbiased search also allows for more quantitative statements to be made about the source population in the region surveyed.

The stereoscopic imaging atmospheric Cherenkov telescope (IACT) array VERITAS has just completed a two-year survey of a 5 by 15 degree portion of the Cygnus region of the Galactic Plane. The Cygnus region was a natural target for survey observations, as it is already known to contain a significant number of potential TeV gamma-ray emitters. In the GeV (20MeV – 300 GeV) energy band, it is home to a number of sources or potential sources, including no less than 4 distinct Fermi sources [3]. Moreover, both Fermi and its predecessor EGRET have detected diffuse emission from this region that is greater in flux than all of the currently resolved sources taken together. Viewed in the energy range between 1TeV-50 TeV, it contains a pair of unidentified TeV sources (MGRO J2031+41 and MGRO 2019+37) detected by the Milagro Gamma Ray Observatory, a water Cherenkov extensive air shower array that is sensitive to TeV sources at a median energy of 20 TeV over the entire sky [4], as well as the unidentified source TeV J2032+4130 (first detected by the HEGRA IACT array[5]), that is spatially coincident with MGRO J2031+41. The exact nature of these sources is currently unknown. There is also a significant catalog of objects detected at other wavelengths, including including SNRs, pulsar wind nebulae (PWNe), high-mass x-ray binaries (HMXBs) and massive star clusters, that are considered potential TeV sources.

II. Survey Observations

Survey observations, which began in April 2007 and were completed in November 2008, cover the field between galactic longitudes $67°$ and $82°$ and galactic latitudes $-1°$ and $4°$ with a grid of pointed observations. Grid points have $0.8°$ separation in Galactic latitude and $1°$ separation in galactic longitude, allowing for substantial overlap in the fields of view for observations at nearby grid points. Approximately one hour of observing time is taken at every grid point (generally within a 1-3 day period), with that hour broken into 20-minute observation periods. Figure 1 shows both a schematic of the survey observation strategy and the acceptance-corrected ("effective") exposure time over the entire survey field. The base survey achieves a relatively uniform effective exposure of ~ 6 hours. The full survey dataset (> 140 hours of good-quality observation time) has regions of enhanced exposure due to follow-up observations (some taken in fall 2008, others scheduled to be taken in spring 2009).

Survey data have been quality-selected to remove runs with unstable trigger rates, poor weather conditions, and known hardware problems. Almost all survey data were taken on moonless nights, with a few percent taken under slight to moderate moonlight conditions. Since survey observations began during the commissioning period for the VERITAS array, data in the survey proper were taken in two different configurations. Observations from spring 2007 were taken with a three-telescope array configuration (including telescopes 1, 2, and 3) and observations from fall 2007 and spring and fall 2008 were taken with the full four-telescope array. Follow-up data taken in fall 2008 were also taken with the four-telescope array configuration; due to a scheduled VERITAS upgrade, any follow-up data taken in Spring 2009 will be taken

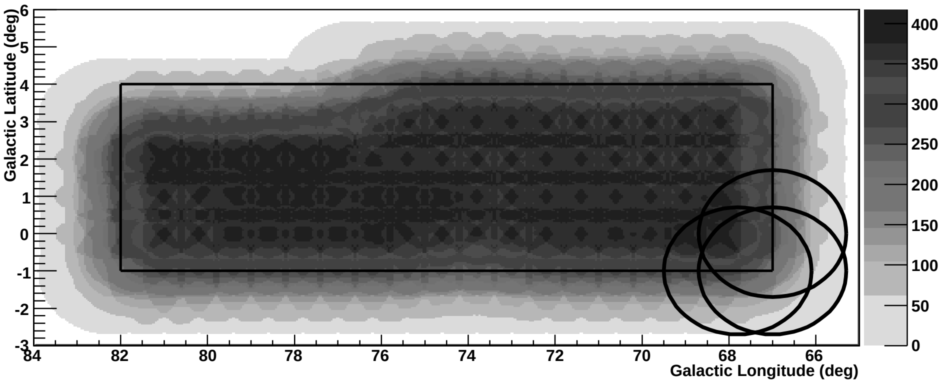

Fig. 1: Effective exposure map for the VERITAS Cygnus sky survey, based on data obtained from Spring 2007 through Fall 2008. The color scale to the right gives the effective exposure time in minutes. The black box indicates the boundary of the survey region proper; the black circles show examples of the overlapping fields of observation that are tiled to produce the survey.

with the three-telescope array configuration containing telescopes 2, 3, and 4.

A. Zenith Angle of Observations

Survey observations were taken over a range of zenith angles between $10°$ to $35°$. Observations were scheduled in such a way as to keep the average zenith angle of observations for any survey pointing at $20°$, but constraints in terms of available time did not always allow for this. We estimate that 45% of the survey region is covered by observations taken at an average zenith angle of $20°$ or smaller, another 33.5% by observations taken at $20° < z < 25°$, 9% by observations taken at $25° < z < 30°$, and 12.5% by observations taken at $z > 30°$.

III. Survey Analysis

Given that the H.E.S.S. survey revealed a population of Galactic TeV gamma-ray emitters that was biased towards hard-spectrum, moderately extended sources[1], and the fact that that the Milagro survey of the Cygnus region [4] showed sources of significant apparent extent, it was reasonable to expect that some or all of the visible gamma-ray sources in this region would also have relatively hard spectra and significant extension.

In order to optimize the survey's sensitivity to such sources while not sacrificing too much in the way of sensitivity to softer-spectrum and/or point-like sources, a set of parallel analyses was used. Each analysis is a variation on a common base analysis, optimized for better sensitivity to a particular type of source. In order to limit the number of additional trials factors incurred, the number of parallel analyses was restricted to four. Two were optimized for sources with a Crab-like spectrum—one for point sources and the other for moderately extended ($r = 0.2°$) sources—and two more were optimized for harder spectrum point-like and extended sources, using a reference source with a power-law spectrum and a spectral index of 2.0.

The completely common elements of the analysis procedure consist of calibrating and cleaning the Cherenkov images and parameterizing them by second moments[6]. The technique used to stereoscopically reconstruct the shower direction and impact parameter is likewise common to all analyses: however, images used in stereoscopic reconstruction are required to exceed a minimum integrated charge (*size*) in digital counts (dc), and the value of that requirement is analysis-specific as shown in Table I.

TABLE I: Cuts Specific to Parallel Analyses

	Point Source	Extended Source
Soft Source	size $>$ 600dc($\sim$ 90p.e.) $\theta^2 < 0.013$	size $>$ 600dc $\theta^2 < 0.05$
Hard Source	size $>$ 1000dc($\sim$ 150p.e.) $\theta^2 < 0.013$	size $>$ 1000dc $\theta^2 < 0.05$

Cosmic ray background is rejected using two means. The first is a pair of variables (*mean scaled length* (MSL) and *mean scaled width* (MSW) that summarize differences in image shape between gamma ray events and the majority of the cosmic ray background)[7] and are applied prior to generation of photon sky maps. The second is a cut on the square of the angular distance (θ^2) between a reconstructed shower and the sky position of a potential source that is applied as part of that process. The cuts on *mean scaled length* and *mean scaled width* are common to all parallel analyses ($0.05 < \mathrm{MSW} < 1.06$, $0.05 < \mathrm{MSL} < 1.24$), while the cut in θ^2 is analysis-specific as shown in Table I. The residual cosmic ray background is estimated using the "ring-background" model [8].

IV. Assessment of Survey Sensitivity

A set of detailed survey simulations, coupled with observations of the Crab Nebula at multiple offsets, allows us to determine the *a priori* sensitivity of the survey analyses, not only to a point source with a

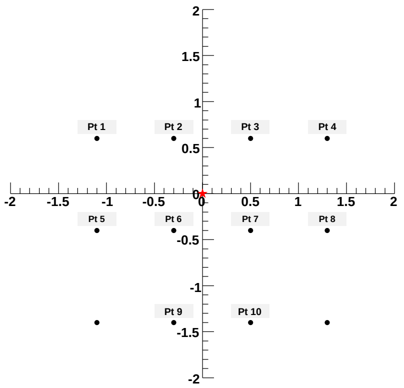

Fig. 2: Structure of the simulated survey grid, with the contributing observation positions numerically labelled. The test point is positioned at the origin.

Crab-like spectrum, but to harder-spectrum and/or significantly extended sources. In order to best reproduce the expected background conditions, blank (i.e. cosmic-ray dominated) survey fields were used to provide the background for these simulations. Blank fields at an appropriate range of zenith angles were pulled from the survey and arranged in a mocked-up 'cell' of the survey grid around a test point, as shown in Figure 2. Showers that reconstruct at a distance greater than $1.7°$ from the center of the field of view are not used in the analysis of survey data. Therefore, only pointings where the center of the field of view is less than $1.7°$ from the test position are included in the simulation, as only these pointings contribute significantly to the sensitivity at the test point.

Simulated gamma rays were then injected into each field in the simulated survey grid at the test position at a rate appropriate to the source spectrum and flux strength in question. In each case the gamma rays were simulated at an appropriate camera offset and matched as closely as possible to the background field in terms of zenith angle and azimuth. In the case of an extended source, the injection positions were smeared by a two-dimensional Gaussian with appropriate radii. The simulated grid is then analyzed using standard survey analysis procedures.

In order to validate this technique, simulated Crab wobble observations, again using survey background fields, were tested for consistency against standard wobble ($0.5°$ offset) and larger-offset Crab data; the predicted rates and sensitivities appear to be in good agreement.

Preliminary results of the sensitivity studies, using a simulated survey grid of $20°$ zenith angle four-telescope observations, have been completed. These suggest that the soft-spectrum point-source survey analysis is sensitive at 5σ or better pre-trials to a source with a spectral index of 2.5 and a flux 3% that of the Crab Nebula; the hard-spectrum point-source survey analysis is likewise sensitive to sources with a spectral index of 2.0 and an integral flux of better than 3% of the Crab Nebula above 200 GeV. Early studies of simulated hard-spectrum extended sources (Gaussian radius of $0.2°$) suggest that the survey analysis optimized for extended, hard-spectrum sources is sensitive to sources with an integral flux of 6% of the Crab Nebula above 200 GeV.

Based on analysis of both simulated survey grids and four-telescope Crab data with one telescope removed from consideration, we estimate that using the three-telescope array configuration causes at most a 10% loss in sensitivity, and affects about one third of the total survey region. The impact of zenith angle on the survey sensitivity is more variable; based on current simulations and Crab data, we do not expect the survey sensitivity to change significantly for regions where the average zenith angle is between $20°$ and $30°$, but we do expect a significant drop in sensitivity for the roughly 12.5% of the survey where the average zenith angle is greater than $30°$.

The interaction of the effects discussed above, as well as the impact of other potential systematic effects on sensitivity (such as the the variation in azimuth angle of observations over the survey region) are still under investigation, but a reasonable estimate still places the point-source sensitivity at better than 4% of the Crab Nebula flux over most of the survey region.

V. Summary

VERITAS has completed a 140-hour survey of a 5 by 15 degree portion of the Cygnus region of the Galactic Plane. Simulation studies indicate that the survey's average VHE flux sensitivity is better than 4% of the Crab Nebula at energies above 200 GeV for point sources, and better than 8% of the Crab Nebula at energies above 200 GeV for extended sources. Further follow-up observations have been scheduled for Spring 2009 on the basis of the preliminary survey analysis, and the final survey maps will be released after these observations have been completed.

VI. Acknowledgments

This research is supported by grants from the U.S. Department of Energy, the US National Science Foundation, and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland, and by STFC in the UK. We acknowledge the excellent work of the technical support staff at the FLWO and the collaboration institutions in the construction and operation of the instrument.

References

[1] Hoppe, S. 2008, International Cosmic Ray Conference, 2, 579
[2] Aharonian, F. A., et al. 2002, A&A, 395, 803
[3] A. A. Abdo *et al.* [Fermi LAT Collaboration], arXiv:0902.1340 [astro-ph.HE].
[4] A. A. Abdo *et al.*, ApJ **664**, L91 (2007)
[5] HEGRA Collaboration: F. Aharonian 2005, arXiv:astro-ph/0501667
[6] Hillas, M. 1985 Proc. of the 19th ICRC (La Jolla, USA) 3, 445

[7] Krawczynski, H., Carter-Lewis, D. A., Duke, C., Holder, J., Maier, G., Le Bohec, S., & Sembroski, G. 2006, Astroparticle Physics, 25, 380

[8] Aharonian, F., *et al* (H.E.S.S. collaboration) 2005, A&A, 430, 865