PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

VTSCat - The VERITAS Catalog of Gamma Ray Observations

Sameer Patel,[a,*] **Gernot Maier**[b] **and Philip Kaaret**[a] **on behalf of the VERITAS Collaboration**
(a complete list of authors can be found at the end of the proceedings)

[a] *University of Iowa,*
Department of Physics and Astronomy, Iowa City, USA
[b] *DESY, Platanenallee 6, 15738 Zeuthen, Germany*
E-mail: sameer-patel-1@uiowa.edu, gernot.maier@desy.de

We present a catalog of results of gamma-ray observations made by VERITAS, published from 2008 to 2020. VERITAS is a ground based imaging atmospheric Cherenkov telescope observatory located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona, sensitive to gamma-ray photons with energies in the range of ~ 100 GeV - 30 TeV. Its observation targets include galactic sources such as binary star systems, pulsar wind nebulae, and supernova remnants, extragalactic sources like active galactic nuclei, star forming galaxies, and gamma-ray bursts, and some unidentified objects. The catalog includes in digital form all of the high-level science results published in 112 papers using VERITAS data and currently contains data on 57 sources. The catalog has been made accessible via GitHub and at NASA's HEASARC.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)812

Figure 1: The VERITAS Array at FLWO Basecamp (https://veritas.sao.arizona.edu)

1. The VERITAS Observatory

Located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona, VERITAS commenced operations using all four telescopes in 2007. Employing the imaging atmospheric Cherenkov observation technique, VERITAS detects VHE gamma rays through the Cherenkov radiation generated in air showers initiated by the interaction of the primary gamma-rays in Earth's atmosphere. The Cherenkov photons are detected using photomultiplier tubes. The stereoscopic use of 4 telescopes leads to improved shower reconstruction and background rejection.

Data Type	**File Formats**	**Keyword**	**Data Description**	**Reference Figure**
Observation Details	yaml	-	Significance, spectral models, etc.	Listing 1
Light Curve	ecsv, png	lc	Integrated gamma ray fluxes vs. time	Listing 2; fig. 2
Spectral Energy Distribution	ecsv, png	sed	Spectral flux points with errors and/or upper limits	Listing 3; fig. 2
Sky Map	fits	signif-skymap, excess-skymap	Statistical significance or excess sky map	-

Table 1: Data Formats in VTSCat

Listing 1: Observation details of Mrk 501 in [1]

```
---
source_id: 91
reference_id: 2017A&A...603A..31A
file_id: 1
telescope: veritas

# VERITAS high (TeV flare  2009 May 1)
spec:
  erange: {min: 0.2, max: 6, unit: TeV}
  mjd: {max: 54955., min: 54952.41}
  model:
```

```
    type: pl
    parameters:
      norm: {val: 4.17, err: 0.24, scale: 1e-11, unit: cm-2 s-1
         TeV-1}
      index: {val: 2.26, err: 0.06}
      e_ref: {val: 1, unit: TeV}
```

2. VTSCat - The VERITAS Data Catalog

The VERITAS Data Catalog (hereafter refered to as VTSCat), is a collection of all the data used in more than 100 papers published by the VERITAS collaboration. The majority of the catalog is compiled from the results of known gamma-ray sources but also includes some results from dark matter studies, measurements of the extragalactic background light, cosmic ray spectra, and upper limits on candidate gamma-ray sources.

Listing 2: Mrk 501 light curve data in [1]

```
# %ECSV 0.9
# ---
# datatype:
# - {name: e_min, unit: TeV, datatype: float64}
# - {name: time, unit: MJD, datatype: float64}
# - {name: flux, unit: cm-2 s-1, datatype: float64}
# - {name: flux_err, unit: cm-2 s-1, datatype: float64}
# meta: !!omap
# - data_type: lc
# - source_id: 91
# - reference_id: 2017A&A...603A..31A
# - telescope: veritas
# - {SED_TYPE: flux}
# - comments: |
#       VERITAS light curve
e_min time flux flux_err
0.30    54907.9710185 6.74707909798e-11 8.84958247235e-12
0.30    54914.8976852 2.97166550106e-11 3.38276780387e-12
0.30    54946.8948611 3.85096002476e-11 9.14725837687e-12
0.30    54951.893044 2.16908417652e-11 5.77378422019e-12
0.30    54952.9114699 1.89636725809e-10 1.22037567454e-11
0.30    54953.7946065 9.6125590747e-11 9.56236260066e-12
0.30    54954.7541319 1.1551067977e-10 2.26421166418e-11
0.30    54955.8014468 8.44464848202e-11 1.85370201643e-11
0.30    54964.6290046 5.97134728089e-11 1.79060782762e-11
0.30    54980.7855324 2.40990545415e-11 8.1438236656e-12
```

```
0.30    54982.8297106  2.35129258185e-11  7.3866746951e-12
0.30    54983.8427778  5.14595146513e-11  1.05960376982e-11
0.30    54994.235669  6.64172364739e-11  1.77361601101e-11
0.30    54995.2250903  4.59656118181e-11  1.07883414089e-11
0.30    54996.2994653  4.49888567164e-11  1.02904552945e-11
0.30    54997.2639329  3.12936163865e-11  1.068283848e-11
0.30    54998.2885972  1.99661168475e-11  9.04910537218e-12
0.30    54999.2805185  1.13290032915e-11  8.65266918864e-12
0.30    55001.2647546  1.61178361422e-11  9.25041021514e-12
0.30    55004.1765255  2.75049516655e-11  8.72583430906e-12
```

Following closely in the footsteps of the structure of GammaCat,[1] VTSCat consists of high level machine and human readable data files in different formats as described in Table 1. Listings 1, 2 & 3 show the formats of some of the data files while Figure 2 shows quicklook plots. An example use of the VTSCat data is shown in Figure 3 which presents all of the spectral energy distributions of Mrk 501 measured by VERITAS.

Listing 3: Mrk 501 spectral energy distribution (SED) data (high state) in [1]

```
# %ECSV 0.9
# ---
# datatype:
# - {name: e_ref, datatype: float32, unit: TeV}
# - {name: dnde, datatype: float32, unit: m-2 s-1 TeV-1}
# - {name: dnde_err, datatype: float32, unit: m-2 s-1 TeV-1}
# meta: !!omap
# - data_type: sed
# - source_id: 91
# - reference_id: 2017A&A...603A..31A
# - file_id: 1
# - telescope: veritas
# - comments: |
#       VERITAS high state
e_ref dnde dnde_err
0.2506   9.39e-06 9.12e-07
0.3972   3.57e-06 3.45e-07
0.6295   1.12e-06 1.23e-07
0.9977   3.66e-07 5.16e-08
1.581   2.03e-07 2.69e-08
2.506   5.18e-08 1.02e-08
3.972   1.61e-08 4.31e-09
```

[1] https://gamma-cat.readthedocs.io/

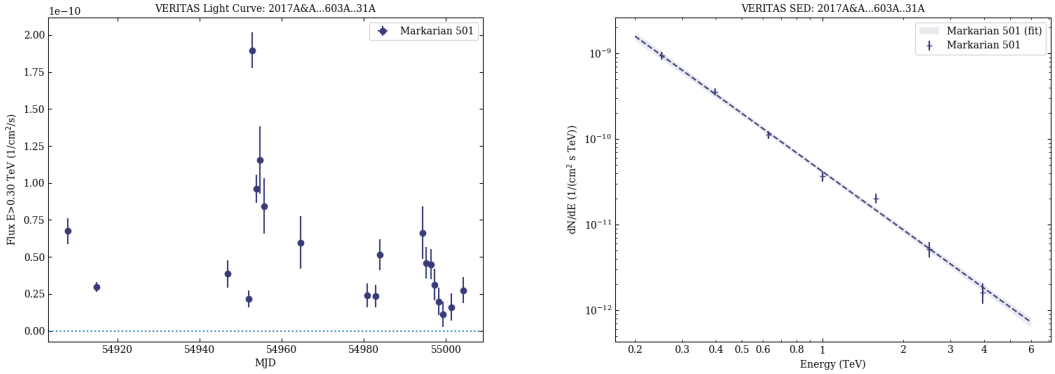

Figure 2: Left: Mrk 501 light curve & Right: Mrk 501 spectral energy distribution generated from VTSCat data files shown in listings (2 & 3)

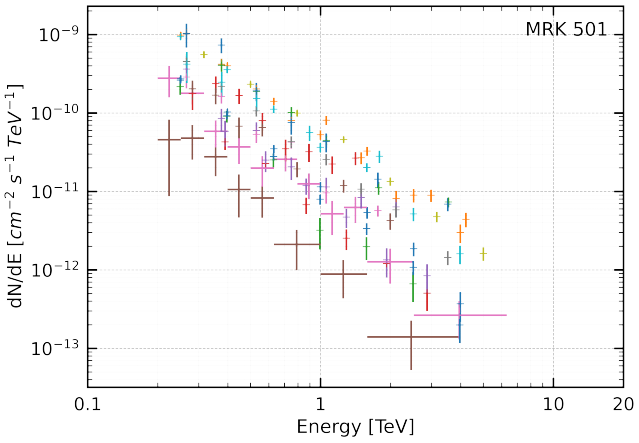

Figure 3: Combined spectral energy distribution (SED) data of Mrk 501 [1–7]

The data catalog is available for public access at the following data repositories:

- GitHub: `https://github.com/VERITAS-Observatory/VERITAS-VTSCat/releases`
- Zenodo [8]: `https://zenodo.org/record/4964083`,
- HEASARC: to be published under `https://heasarc.gsfc.nasa.gov/W3Browse/all/verimaster.html`.

Each data file contains the appropriate data units that can be read through Astropy [9, 10]. The data in VTSCat on Github & Zenodo has been organized by year and publication, using ADS bibcodes[2] as reference identifiers. The different objects are then identified by the `src_id` (source id), which is an integer value. The description files for these objects can be found in the `Source` folder. One can then choose the required type of data in the folder by identifying the data file format

[2]https://ui.adsabs.harvard.edu/help/actions/bibcode

as in table 1. As an example, to get to the lightcurve data of MRK 501 (as in listing 2), the absolute path would be `/2017/2017A&A...603A..31A/VER-000091-lc.ecsv`.

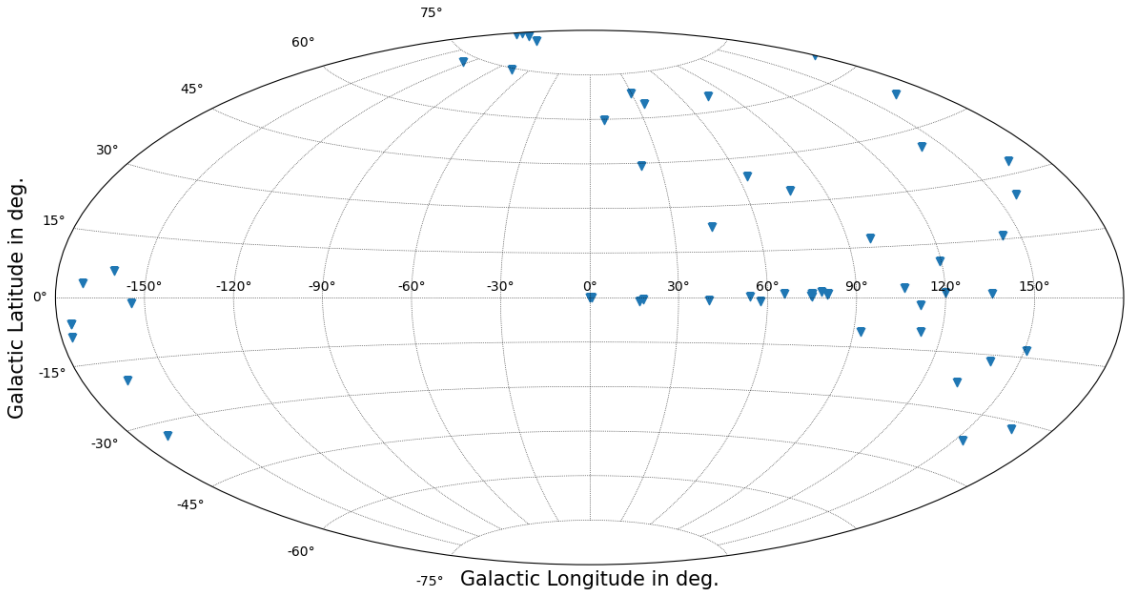

Figure 4: An Aitoff projection of gamma-ray sources detected[3] by VERITAS

The README file provides the catalog observation schema, object names, data files, ADS references, etc. and the Formats and Models and Spectral Models files provide information about data types and the spectral models of the yaml files respectively.

3. Catalog Statistics

Currently, VTSCat contains data on 57 gamma-ray sources collected between 2008 and 2020, some with multiple observational datasets. The skymap of VERITAS detected sources is shown in Fig. 4. We also include a number of statistical plots relating to published papers in `ADSdata`, some of which can be seen in Fig. 5. The plot on the left shows the number of publications vs. the statistical significance of the excess of the source (expressed in sigma). Sources with $sigma < 5$ include variables sources, sources with upper limit measurements or those without a VERITAS detection of the known TeV sources. The plot on the right shows the number of publications against the observation time of the source (in hours) as reported by authors in the corresponding papers. The catalog repositories listed in section 2 will be updated periodically as VERITAS collaboration authors publish papers on new and existing VERITAS sources.

[3] as published in papers

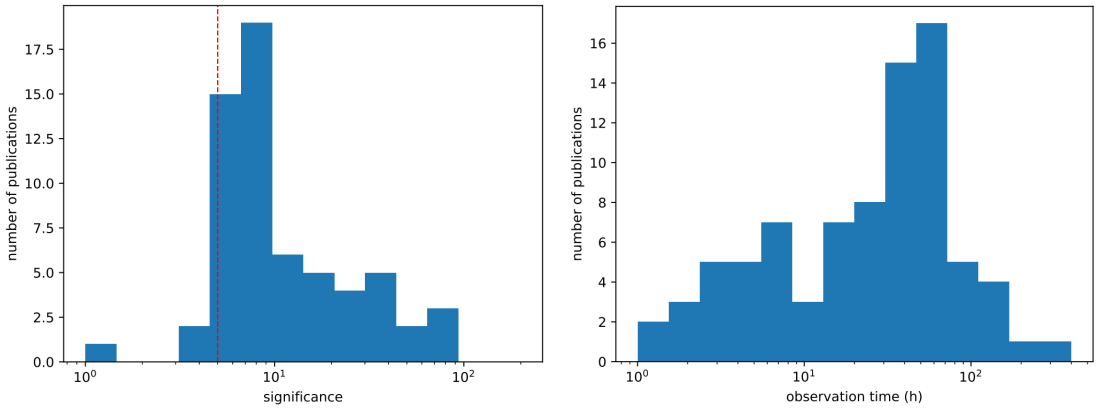

Figure 5: Number of VERITAS publications vs. significance with the dotted line as the VERITAS publication threshold (left) and observation time (right)

4. Summary

In this proceeding we have presented the VTSCat, an actively updated, publicly accesible and a machine/human readable catalog of the results from the VERITAS array. It is our hope that in making 12 years of VERITAS data more easily accessible, it can be easily integrated and help to enhance the work of future publications within the community.

Acknowledgments

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, and by the Helmholtz Association in Germany. This research used resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science, and resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

References

[1] M.L. Ahnen, S. Ansoldi, L.A. Antonelli, P. Antoranz, A. Babic, B. Banerjee et al., *Multiband variability studies and novel broadband SED modeling of Mrk 501 in 2009*, *Astron. & Astrophys.* **603** (2017) A31 [1612.09472].

[2] A.A. Abdo, M. Ackermann, M. Ajello, A. Allafort, L. Baldini, J. Ballet et al., *Insights into the High-energy γ-ray Emission of Markarian 501 from Extensive Multifrequency Observations in the Fermi Era*, *Astrophys. J.* **727** (2011) 129 [1011.5260].

[3] V.A. Acciari, T. Arlen, T. Aune, M. Beilicke, W. Benbow, M. Böttcher et al., *Spectral Energy Distribution of Markarian 501: Quiescent State Versus Extreme Outburst*, *Astrophys. J.* **729** (2011) 2 [1012.2200].

[4] J. Aleksić, S. Ansoldi, L.A. Antonelli, P. Antoranz, A. Babic, P. Bangale et al., *Multiwavelength observations of Mrk 501 in 2008*, *Astron. & Astrophys.* **573** (2015) A50 [1410.6391].

[5] E. Aliu, S. Archambault, A. Archer, T. Arlen, T. Aune, A. Barnacka et al., *Very high energy outburst of Markarian 501 in May 2009*, *Astron. & Astrophys.* **594** (2016) A76 [1608.01569].

[6] M.L. Ahnen, S. Ansoldi, L.A. Antonelli, P. Antoranz, A. Babic, B. Banerjee et al., *Multiband variability studies and novel broadband SED modeling of Mrk 501 in 2009*, *Astron. & Astrophys.* **603** (2017) A31 [1612.09472].

[7] A. Furniss, K. Noda, S. Boggs, J. Chiang, F. Christensen, W. Craig et al., *First NuSTAR Observations of Mrk 501 within a Radio to TeV Multi-Instrument Campaign*, *Astrophys. J.* **812** (2015) 65 [1509.04936].

[8] W. Benbow, A. Brill, M. Capasso, J. Christiansen, M. Errando, A. Falcone et al., *VTSCat: The VERITAS Catalog of Gamma-Ray Observations*, Apr., 2021. 10.5281/zenodo.4964083.

[9] Astropy Collaboration, T.P. Robitaille, E.J. Tollerud, P. Greenfield, M. Droettboom, E. Bray et al., *Astropy: A community Python package for astronomy*, *Astron. & Astrophys.* **558** (2013) A33 [1307.6212].

[10] Astropy Collaboration, A.M. Price-Whelan, B.M. Sipőcz, H.M. Günther, P.L. Lim, S.M. Crawford et al., *The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package*, *Astron. J.* **156** (2018) 123 [1801.02634].

Full Authors List: VERITAS Collaboration

C. B. Adams[1], A. Archer[2], W. Benbow[3], A. Brill[1], J. H. Buckley[4], M. Capasso[5], J. L. Christiansen[6], A. J. Chromey[7], M. Errando[4], A. Falcone[8], K. A. Farrell[9], Q. Feng[5], G. M. Foote[10], L. Fortson[11], A. Furniss[12], A. Gent[13], G. H. Gillanders[14], C. Giuri[15], O. Gueta[15], D. Hanna[16], O. Hervet[17], J. Holder[10], B. Hona[18], T. B. Humensky[1], W. Jin[19], P. Kaaret[20], M. Kertzman[2], T. K. Kleiner[15], S. Kumar[16], M. J. Lang[14], M. Lundy[16], G. Maier[15], C. E McGrath[9], P. Moriarty[14], R. Mukherjee[5], D. Nieto[21], M. Nievas-Rosillo[15], S. O'Brien[16], R. A. Ong[22], A. N. Otte[13], S. R. Patel[15], S. Patel[20], K. Pfrang[15], M. Pohl[23,15], R. R. Prado[15], E. Pueschel[15], J. Quinn[9], K. Ragan[16], P. T. Reynolds[24], D. Ribeiro[1], E. Roache[3], J. L. Ryan[22], I. Sadeh[15], M. Santander[19], G. H. Sembroski[25], R. Shang[22], D. Tak[15], V. V. Vassiliev[22], A. Weinstein[7], D. A. Williams[17], and T. J. Williamson[10]

[1]Physics Department, Columbia University, New York, NY 10027, USA [2]Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA [3]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA [4]Department of Physics, Washington University, St. Louis, MO 63130, USA [5]Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA [6]Physics Department, California Polytechnic State University, San Luis Obispo, CA 94307, USA [7]Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA [8]Department of Astronomy and Astrophysics, 525 Davey Lab, Pennsylvania State University, University Park, PA 16802, USA [9]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland [10]Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA [11]School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA [12]Department of Physics, California State University - East Bay, Hayward, CA 94542, USA [13]School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street NW, Atlanta, GA 30332-0430 [14]School of Physics, National University of Ireland Galway, University Road, Galway, Ireland [15]DESY, Platanenallee 6, 15738 Zeuthen, Germany [16]Physics Department, McGill University, Montreal, QC H3A 2T8, Canada [17]Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA [18]Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA [19]Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA [20]Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA [21]Institute of Particle and Cosmos Physics, Universidad Complutense de Madrid, 28040 Madrid, Spain [22]Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA [23]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany [24]Department of Physical Sciences, Munster Technological University, Bishopstown, Cork, T12 P928, Ireland [25]Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA

PoS(ICRC2021)812