

VTSCat - The VERITAS Catalog of Gamma Ray Observations

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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.

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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 referred 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: dnnde, datatype: float32, unit: m-2 s-1 TeV-1}
# - {name: dnnde_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 dnnde dnnde_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/>

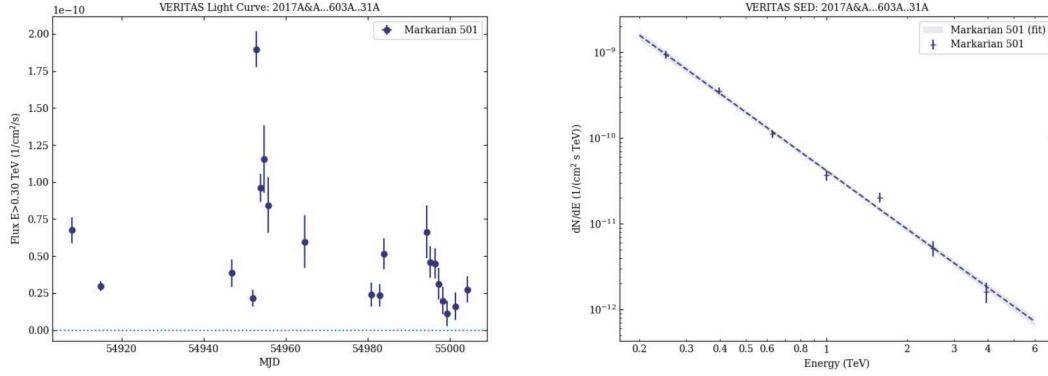


Figure 2: Left: Mrk 501 light curve & Right: Mrk 501 spectral energy distribution generated from VTSCat data files shown in listings (2 & 3)

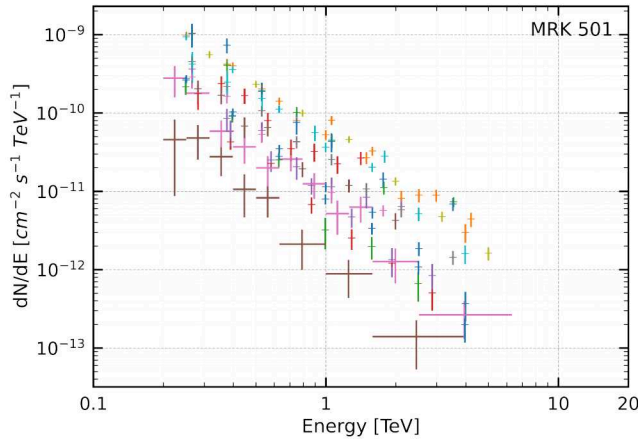


Figure 3: Combined spectral energy distribution (SED) data of Mrk 501 [1–7]

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 bibcodes² 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-000091-1c.ecsv`.

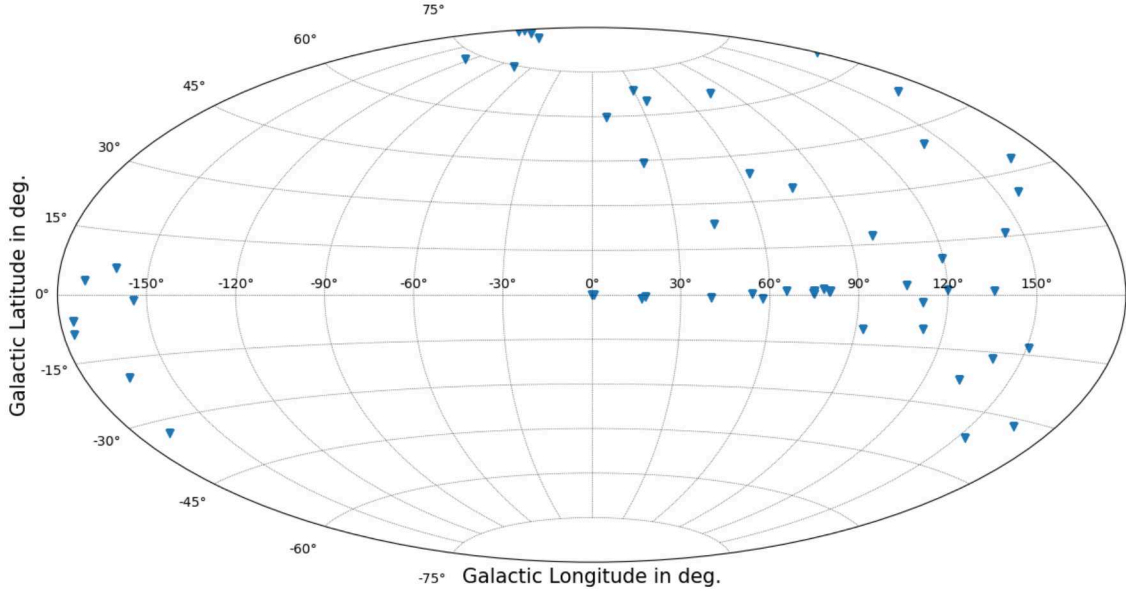


Figure 4: An Aitoff projection of gamma-ray sources detected³ by VERITAS

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 σ). 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.

³as published in papers

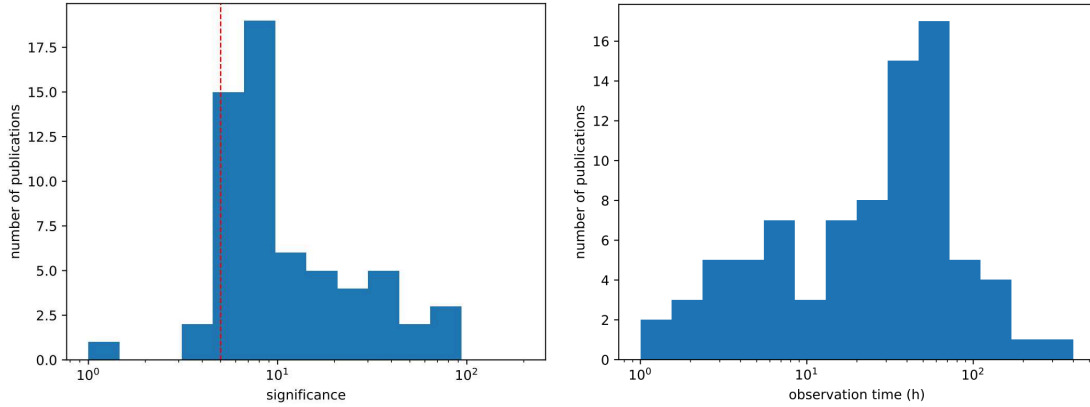


Figure 5: Number of VERITAS publications vs. significance with the dotted line as the VERITAS publication threshold (left) and observation time (right)

4. Summary

In this proceeding we have presented the VTSCat, an actively updated, publicly accessible 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.

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