

Public Data Release 2

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An overview of ZTF and the science objectives is given in [Bellm et al. 2019](#) and [Graham et al. 2019](#). The ZTF Science Data System (ZSDS) is housed at [IPAC/Caltech](#) and is described in [Masci et al. 2019](#). This page provides a summary and quick guide to the ZTF Public DR2 products.

Please familiarize yourself with all advisories highlighted in red before accessing and using the products.

[Click to jump to the Data Access & Recipes section.](#)

1. Summary of the ZTF Surveys

ZTF observing time is split three ways:

- (i) The Public Survey (40%);
- (ii) Private Collaboration and Partnership Surveys (40%);
- (iii) Programs granted by the Caltech Time Allocation Committee (20%).

Funding is provided by both the ZTF collaboration and the U.S. National Science Foundation through the Mid-Scale Innovations Program (MSIP).

The Public Survey in particular enables a wide range of community science and constitutes the following:

- A Northern-equatorial sky survey: a three-night cadence of the Northern sky visible from Palomar Observatory (≈ 2.5 to 3π steradians), comparable to the LSST wide-fast-deep cadence, irrespective of Galactic latitude. This component surveys $\approx 15,000$ to $20,000$ square degrees every three nights.
- A Galactic plane-targeted survey: a one-night cadence survey of the Galactic plane at $|b| \leq 7^\circ$ and $\text{Dec.} > \sim -25^\circ$, whenever a survey-field falls in this footprint. The area covering this footprint is seasonal and varies from ~ 1000 to 2000 square degrees.
- For each of the above surveys, there is one g -filter and one r -filter exposure of the same pointing separated by at least 40 minutes.

1.a. Acknowledging ZTF and Referencing Data Product usage

For publications that use ZTF Science Data Products, please include the following text in your acknowledgments:

Based on observations obtained with the Samuel Oschin 48-inch Telescope at the Palomar Observatory as part of the Zwicky Transient Facility project. ZTF is supported by the National Science Foundation under Grant No. AST-1440341 and a collaboration including Caltech, IPAC, the Weizmann Institute for Science, the Oskar Klein Center at Stockholm University, the University of Maryland, the University of Washington, Deutsches Elektronen-Synchrotron and Humboldt University, Los Alamos National Laboratories, the TANGO Consortium of Taiwan, the University of Wisconsin at

Furthermore, we appreciate you citing the following publication:

Masci, F. J., Laher, R. R., Rusholme, B., et al. 2018, *The Zwicky Transient Facility: Data Processing, Products, and Archive*, PASP, 131, 995.

2. Scope of this Release

The Second ZTF Public Data Release (DR2) builds upon the [First Data Release \(DR1\)](#) to include products from (i) an additional six months of data acquired under the [Public Survey](#) (+ January to June 2019) and (ii) data acquired under [Private Survey](#) time (from both partnership and Caltech programs) from approximately the first 3.4 months of science operations (~ March to June 2018). The latter is included due to the 18 month embargo being lifted on the products.

More specifically, DR2 includes the following:

1. [Single Exposure Products](#) associated with individual science observation epochs (lightcurve epochs) in *g* and *r* filters only satisfying:
 - o Program ID = 1: implying products from the **Public Survey**, FOR:
 - o Observation MJD \geq 58194.0 (= 2018-03-17 00hrs UTC), AND
 - o Observation MJD \leq 58664.0 (= 2019-06-30 00hrs UTC), AND
2. [Single Exposure Products](#) associated with individual science observation epochs (lightcurve epochs) in *g*, *r*, and *i* filters satisfying:
 - o Program IDs = 2 and 3: implying products from the **Private Surveys**, FOR:
 - o Observation MJD \geq 58194.0 (= 2018-03-17 00hrs UTC), AND
 - o Observation MJD \leq 58299.0 (= 2018-06-30 00hrs UTC), AND
3. All [Reference \(co-add\) Image Products](#) available in the ZTF Archive as of November 20, 2019 (when products were frozen). Only good quality science exposures from all survey programs, irrespective of the epoch spans above, were included in the co-adds.

NOTE: The public distribution of transient alerts extracted from difference images constructed from products (1) and (3) above [commenced on June 4, 2018](#). These alerts continue to be generated and distributed using new (unreleased) image data from the [Public Survey](#).

3. Summary of Data Products

In accord with the criteria for data-inclusion in [Section 2](#), the following products are available in DR2:

- Raw CCD-based image data files and metadata in FITS format.
- CCD-quadrant-based calibration image data and metadata in FITS format.
 - o Stacked bias images.
 - o Relative pixel-responsivity maps (flatfield corrections).
 - o Bad-pixel masks derived from these calibrations.
- Instrumentally calibrated CCD-quadrant-based, single-exposure science images, source-catalogs, and metadata; specifically:
 - o Science images with astrometric and photometric calibration solutions, and QA information.
 - o Corresponding bit-mask images.
 - o PSF templates (image and look-up-table) for each science image.
 - o Source-catalog FITS-table files containing exclusively PSF-fit photometry measurements.
 - o Source-catalog FITS-table files containing exclusively concentric aperture photometry & source-shape metrics.
 - o Difference images constructed in the sense: "science (single-exposure) image *minus* reference image". For DR2, these are only available for science images that had a preexisting reference image when the science image was first processed.
 - o Effective PSF template for difference image.
 - o Tar file of *already publicly-released* alert packet files (in *Avro* format) corresponding to the CCD-quadrant.
 - o Processing log files.
- Reference Images (co-added/stacked single-exposures) per CCD-quadrant, source-catalogs, and metadata; specifically:
 - o Co-add images with astrometric and photometric calibration solutions, and QA information.
 - o Corresponding pixel-uncertainty images.
 - o Corresponding pixel depth-of-coverage images (recording effective number of input exposures per pixel).
 - o Source-catalog FITS-table files containing exclusively PSF-fit photometry measurements.
 - o Source-catalog FITS-table files containing exclusively concentric aperture photometry & source-shape metrics.
 - o Processing log files.
- Objects (database) Table storing sources from all Reference Image PSF-fit-based catalog files.
 - o Includes "collapsed-lightcurve" metrics (from prior position-matching of *detected* sources across all overlapping, CCD-quadrant-based exposures in the public survey).
 - o This table facilitates initial object-position searches and filtering on any of the lightcurve-collapsed metrics for subsequent extraction of lightcurve data.
- A datastore of lightcurves containing additional metrics at the single-epoch (exposure) level. This is searchable by interfacing with queries on the Objects Table. Lightcurve data can be visualized and downloaded via a GUI or API ([Sections 12a and 12b](#)).
- Entire lightcurve holdings packaged into gzipped tar files ([Section 12c](#))

For details on data and file formats, associated ancillary products, product construction and usage, see the [ZSDS Explanatory Supplement](#). See [Section 10 below](#) for a list of **MUST READ ADVISORIES** about these products. See [Section 11 below](#) for a more detailed list of advisories and known caveats.

4. File-based Product Statistics

The ZTF camera consists of 16 CCDs, each of which is partitioned into 4 readout quadrants. Therefore, [64 CCD-quadrant images are generated per ZTF exposure](#). [A CCD-quadrant is the basic image-unit for pipeline processing and from which all science data products are derived](#). A CCD-quadrant covers $\approx 0.854^\circ \times 0.854^\circ$ on the sky. Table 1 summarizes the CCD-quadrant-based (single exposure) image counts. The second column shows the number of full camera exposures from which these were generated. The CCD-quadrant image counts are separated into "bad" (probably unusable due to non-photometric conditions) and "good" images. The criteria used to identify "bad" vs "good" images are described in Section 2.4 of the [ZSDS Advisories & Cautionary Notes](#). The relative fractions of bad and good images in this table provides an indicator of the overall fraction of "bad" (likely suspect) single-epoch photometry measurements within individual lightcurves.

Table 1: Number of exposures and "good / bad" CCD-quadrant-based science images in DR2

Filter(s)	#Exposures	#Good (usable)	#Bad (suspect)	Total number	Bad / Total [%]
<i>g</i>	54,477	3,088,885	198,410	3,287,295	6.03
<i>r</i>	58,127	3,236,044	247,088	3,483,132	7.09
<i>i</i>	1,871	99,876	3,721	103,597	3.59
<i>g + r + i</i>	114,475	6,424,805	449,219	6,874,024	6.53

The number of CCD-quadrant-based reference images (co-adds) per filter in DR2 are shown in Table 2. **Note:** unless brought to our attention, all of these are expected to have good photometric and astrometric quality in general. This is because they were constructed from good-quality single-exposure images satisfying a range of criteria, which are more stringent than those used to tag the "good" images in Table 1. The criteria used to select inputs for generating reference images are described in Section 6.7 of the [ZSDS Explanatory Supplement](#).

The existence of a reference image for a specific survey field, CCD-quadrant, and filter is important since it means that for this region of sky: (i) image differencing and alerts can be triggered, and (ii) objects can be extracted and then used as seeds to generate lightcurves. The third column in Table 2 shows the percentage of ZTF survey fields/CCD-quadrants with at least 15 single-exposure images (regardless of quality) that have a reference image. 15 *good-quality* images is the minimum number to generate a reference image. These percentages are < 100 since a number of fields/CCD-quadrants do not yet have ≥ 15 *good-quality* science images. These fields are not visited as often during the survey.

Table 2: Number of CCD-quadrant-based Reference Images and visited-sky coverage in DR2

Filter(s)	#Reference Images	Visited-sky coverage [%]
<i>g</i>	57,337	96.95
<i>r</i>	62,651	95.52
<i>i</i>	14,867	88.05
<i>g + r + i</i>	134,855	95.23

5. Source and Lightcurve Statistics

Table 3 reports the number of sources in all PSF-fit-based and aperture-based catalog file products (summarized in [Section 3](#)), separately for single-exposure (*sci*) images and reference (*ref* or co-add) images. The PSF-fit and aperture catalogs are treated independently (with no merging or cross-linking of records) in the Data System. This means a large fraction of the same sources are present in both flavors of catalog. The PSF-fit-based catalogs contain more sources since first, PSF-fitting generally yields more accurate photometry at faint fluxes and hence is more sensitive, and second, it includes deblending of closely-separated sources. Deblending is more important in high source-density regions such as the Galactic plane.

Only sources from the [PSF-fit-based sci](#) catalogs are positionally-matched across observation epochs to construct lightcurves (see Table 4 for numbers). As mentioned above, sources in the deeper PSF-fit-based *ref* catalogs are initially used as seeds to trigger source-matching and generate lightcurves.

Table 3: Number of sources in CCD-quadrant-based catalog files in DR2, according to extraction and image type

Filter(s)	#PSFcat- <i>sci</i> sources	#Aperturecat- <i>sci</i> sources	#PSFcat- <i>ref</i> sources	#Aperturecat- <i>ref</i> sources
<i>g</i>	34,799,157,939	22,008,868,967	2,053,507,697	656,772,487
<i>r</i>	64,698,158,346	40,249,465,415	2,954,247,127	1,013,085,916
<i>i</i>	868,042,655	495,178,759	557,831,277	163,240,538
<i>g + r + i</i>	100,365,358,940	62,753,513,141	5,565,586,101	1,833,098,941

Table 4 reports the number of lightcurves from positional-matching of sources in the single-exposure PSF-fit-based science catalogs with length (number of independent epochs) greater than some limit. The distribution in the number of observation epochs and corresponding timespans is shown in [Figure 3](#). All observation epochs, regardless of data quality are included in the counts in Table 4. For an estimate of the average fraction of "bad" epochs *per lightcurve* (with likely suspect and unusable photometry), see [Table 1](#). The criteria used to identify "bad" vs "good" epochal data are described in Section 2.4 of the [ZSDS Advisories & Cautionary Notes](#).

Table 4: Number of lightcurves with number of DR2 observation epochs (N_{obs}) greater than some limit

Filter(s)	#lightcurves with $N_{obs} \geq 1$	#lightcurves with $N_{obs} \geq 2$	#lightcurves with $N_{obs} \geq 5$	#lightcurves with $N_{obs} \geq 10$	#lightcurves with $N_{obs} \geq 20$
<i>g</i>	842,336,216	688,078,153	544,738,590	465,644,983	375,217,175
<i>r</i>	1,413,965,706	1,189,124,111	949,233,735	786,798,231	623,969,068

i	108,853,073	78,026,346	50,717,481	21,792,536	0
$g + r + i$	2,365,154,995	1,955,228,610	1,544,689,806	1,274,235,750	999,186,243

6. DR2 Sky Coverage

Figure 1 shows the approximate spatial distribution in the number of single-exposure epochs in each filter included in DR2, as Aitoff-Hammer projections in Galactic coordinates. These are approximate since the spatial resolution (bin size) of each map is 1° while a CCD-quadrant subtends $\approx 0.854^\circ \times 0.854^\circ$ at the center of a map. The small-scale dark regions are not holes in coverage, but due to aliasing from the warped reprojection and resampling of CCD-quadrant centers onto larger scales. The presence of ~ 3 arcmin gaps between the camera's CCDs also contributes to these holes.

FITS-formatted image representations of Figure 1 with Word Coordinate System metadata in their headers can be downloaded for each filter:

- g -filter single-exposure coverage map: [sciimage_galcovmap_dr2_g.fits](#)
- r -filter single-exposure coverage map: [sciimage_galcovmap_dr2_r.fits](#)
- i -filter single-exposure coverage map: [sciimage_galcovmap_dr2_i.fits](#)

These maps can be visualized using a FITS-image viewer to determine if a specific sky-position is covered by a survey-field/CCD-quadrant. If so, the approximate number of overlapping epochs on/near this position (to within $\approx 1^\circ$) can be determined from examining the pixel values.

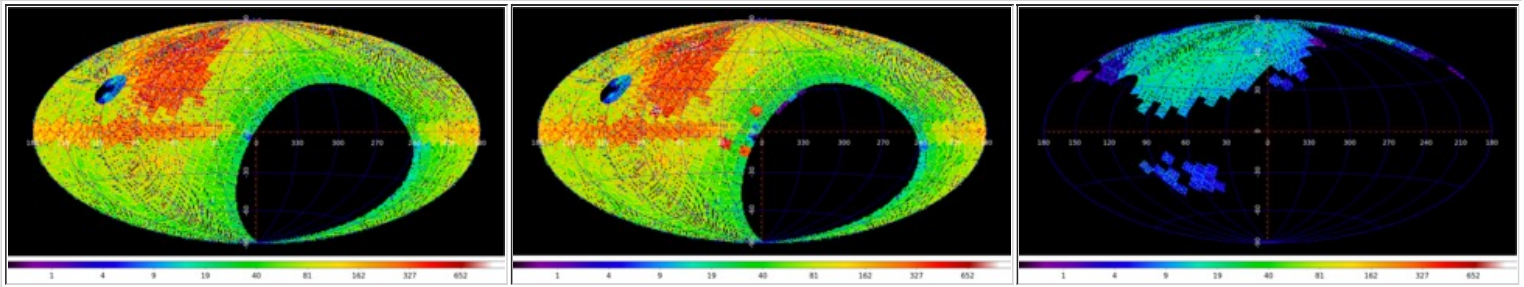


Figure 1 - Sky coverage and number of observation epochs per approximate CCD-quadrant footprint represented in DR2, in Galactic coordinates centered at $l, b = 0, 0$. **Left:** g -filter; **Center:** r -filter; **Right:** i -filter. Color bar represents the number of observation epochs. Dark regions on small scales are not holes in coverage, but due to the coarse resampling of CCD-quadrant centers on 1° scales. This resampling also distorts the true number of epochs per pointing (see Figure 3a for the true epoch distribution). **Click on a panel to enlarge.**

Figure 2 shows the approximate spatial distribution in CCD-quadrants per filter from which lightcurves were generated for inclusion in DR2. These maps closely track the Reference Image coverage since (PSF-catalog-based) sources extracted therefrom were used as seeds to trigger the lightcurve generation. As in Figure 1, these maps are approximate due to their finite spatial resolution (bin size) of 1° compared to the remapped CCD-quadrants that subtend $\approx 0.854^\circ \times 0.854^\circ$ at the center of a map. The small-scale dark regions are not holes in coverage, but due to aliasing from the warped reprojection and resampling of CCD-quadrant centers onto larger scales. The presence of ~ 3 arcmin gaps between the camera's CCDs also contributes to these holes.

FITS-formatted image representations of Figure 2 with Word Coordinate System metadata in their headers can be downloaded for each filter:

- g -filter lightcurve (and \approx Reference Image) coverage map: [matchfile_galcovmap_dr2_g.fits](#)
- r -filter lightcurve (and \approx Reference-Image) coverage map: [matchfile_galcovmap_dr2_r.fits](#)
- i -filter lightcurve (and \approx Reference-Image) coverage map: [matchfile_galcovmap_dr2_i.fits](#)

These maps can be visualized using a FITS-image viewer to determine if a specific position is covered by a survey field/CCD-quadrant. If so, one can determine if lightcurves (and/or Reference Images) exist on/near this position, to within $\approx 1^\circ$.

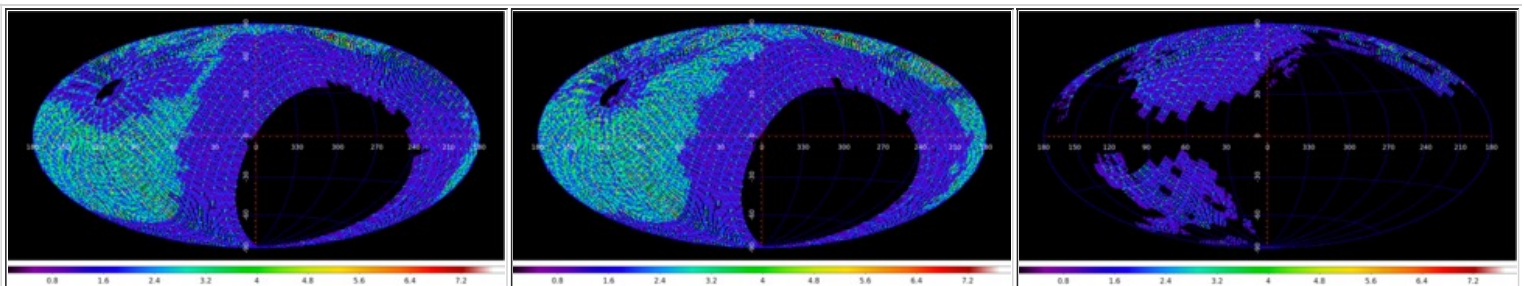


Figure 2 - Spatial distribution representing lightcurve (and \approx Reference Image) coverage in DR2, binned on approximate CCD-quadrant scales, in Galactic coordinates centered at $l, b = 0, 0$. **Left:** g -filter; **Center:** r -filter; **Right:** i -filter. The color bar does not represent the number of observation epochs, but the number of neighboring CCD-quadrants that happen to overlap due to the fixed sky-tiling and coarse resampling of their centers on 1° scales. **Click on a panel to enlarge.**

7. Lightcurve products: timespans, cadence, and epoch distributions

To complement the epoch-coverage maps in [Figure 1](#) and lightcurve numbers in [Table 4](#), Figure 3 shows the distribution in overall timespan per survey-field (latest *minus* earliest exposure in DR2) versus the number of observation epochs in each.

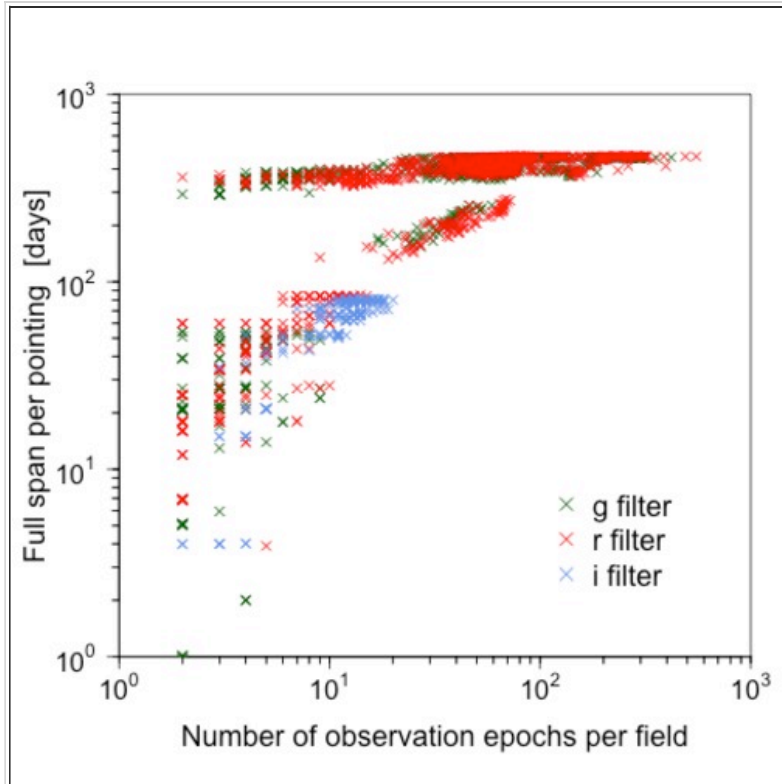


Figure 3 - Timespan of observations per survey-field as a function of the number of epochs in each. These timespans are proxies for the overall spans of lightcurves in DR2.

Figure 4 encapsulates the available timespans and cadences (separation between consecutive epochs) in DR2, for each filter. These plots can be used as follows: for a given observation or effective lightcurve timespan per survey field (or pointing), one would take a horizontal slice to infer the distribution of visit separations (cadences) therein. The number of times a lightcurve is sampled at that cadence is indicated by the color bar. The bins located at lower right (timespans $\ll 90$ days) represent data from the [partnership and Caltech \(private\) surveys](#). DR2 includes approximately the first 3.4 months of data from these programs due to the 18 month embargo being lifted. The *i*-filter data included in DR2 was acquired only under these private programs.

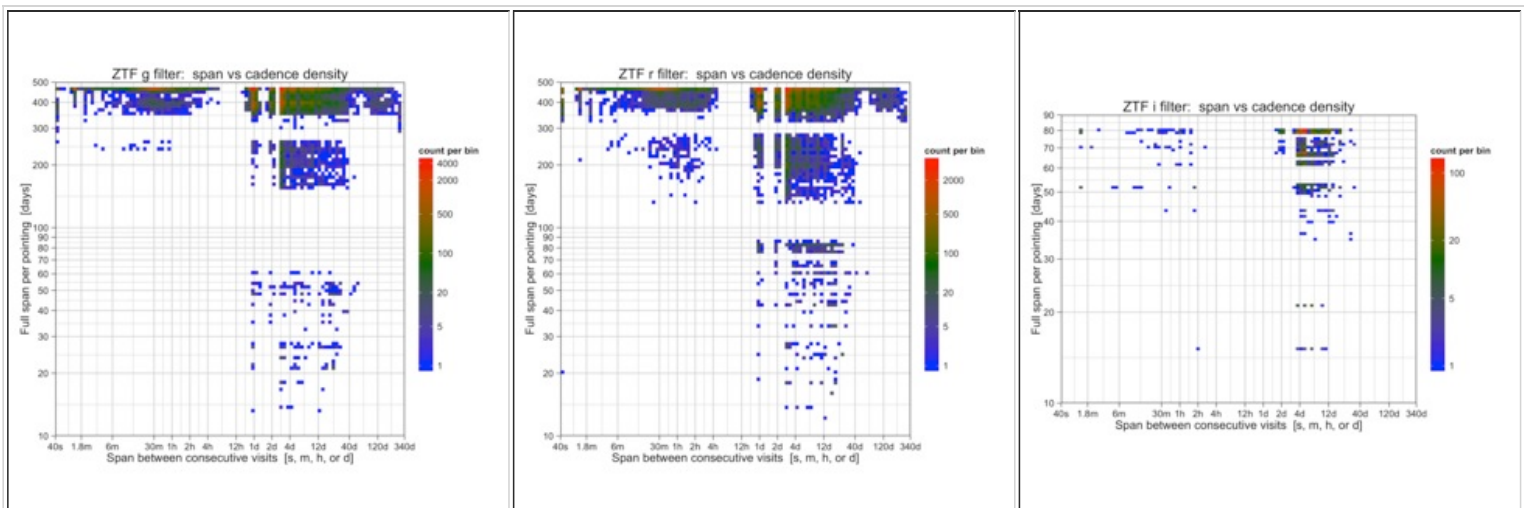


Figure 4 - Effective timespan per pointing (per $\approx 7^\circ \times 7^\circ$ survey field) versus visit cadence. See text above for details. **Left:** *g*-filter; **Center:** *r*-filter; **Right:** *i*-filter. [Click on a panel to enlarge.](#)

8. File-based Product Listings in Archive

8.a. Single-Exposure Image Products

The following is a gzipped text file listing some metadata and the archive path/filenames of all single-exposure science image files in DR2: [DR2_sci_data.txt.gz](#) (932 MB uncompressed).

The columns in this file are: *internal productID*; *Observation JD [days]*; *Center R.A. [decimal degrees]*; *Center Dec. [decimal degrees]*; *archive path/filename of primary science image*. Some of these columns are also present in the archive metadata database to support more generic spatial queries (see [Section 12](#)).

Any archive path/filename in the above file can be prepended with the following root URL to access and download the specific *sciimg.fits* file: <https://irsa.ipac.caltech.edu/ibe/data/ztf/products/>

For example, the first listed science image has URL:

https://irsa.ipac.caltech.edu/ibe/data/ztf/products/sci/2018/0325/251921/ztf_20180325251921_000314_zg_c03_o_q3_sciimg.fits

Alternatively, the *sciimg.fits* suffix can be replaced with any of the following ancillary file suffixes, with products summarized in [Section 3](#):

```
mskimg.fits - bit-mask image corresponding to sciimg.fits
psfcats.fits - PSF-fit source catalog for sciimg.fits
sexcats.fits - aperture-based (SExtractor) photometry catalog for sciimg.fits
sciimgdao.psf - PSF for sciimg.fits in DAOPhot look-up-table format
sciimgdao.psfcent.fits - PSF stamp at center of sciimg.fits
scimrefdiffimg.fits.fz - difference image in fpack'd FITS format
diffimgpsf.fits - effective PSF stamp for difference-image
alerts.tar.gz - gzipped tar-directory of all alert packets
sciimglog.txt - processing log for sciimg.fits (instrumental calibration)
diffimglog.txt - processing log for difference image and event extraction
log.txt - overall processing log for realtime pipeline run
```

8.b. Reference Image Products

The following is a gzipped text file listing some metadata and the archive path/filenames of all Reference Image files in DR2: [DR2_ref_data.txt.gz](#) (21 MB uncompressed).

The columns in this file are: *internal referenceID*; *number of science images co-added*; *5 σ limiting magnitude*; *observation JD of earliest input science image*; *observation JD of latest input science image*; *Center R.A. [decimal degrees]*; *Center Dec. [decimal degrees]*; *archive path/filename of primary reference image*. Some of these columns are also present in the archive metadata database to support more generic spatial queries (see [Section 12](#)).

Any archive path/filename in the above file can be prepended with the following root URL to access and download the specific *refimg.fits* file: <https://irsa.ipac.caltech.edu/ibe/data/ztf/products/>

For example, the first listed reference image has URL:

https://irsa.ipac.caltech.edu/ibe/data/ztf/products/ref/000/field000872/zr/ccd04/q2/ztf_000872_zr_c04_q2_refimg.fits

Alternatively, the *refimg.fits* suffix can be replaced with any of the following ancillary file suffixes, with products summarized in [Section 3](#):

```
refcov.fits - pixel depth-of-coverage image
refunc.fits - pixel (1 $\sigma$ ) uncertainty image
refpsfcats.fits - PSF-fit source catalog for refimg.fits
refsexcats.fits - aperture-based (SExtractor) photometry catalog for refimg.fits
refimglog.txt - processing log for sciimg.fits (instrumental calibration)
log.txt - overall processing log for realtime pipeline run
```

8.c. Other File Products

Other relevant root URLs to access file-based products in DR2 are as follows.

The root URL to access raw CCD-based image files is: <https://irsa.ipac.caltech.edu/ibe/data/ztf/products/raw/>

The root URL to access calibration (cal) related files is: <https://irsa.ipac.caltech.edu/ibe/data/ztf/products/cal/>

For a description of all path and filename identifiers, see Section 7 of the [ZSDS Explanatory Supplement](#).

9. Epoch-based Data Quality Flags and Filtering

The ZTF Observing System is fully robotic. One limitation is that it cannot determine in advance when conditions are non-photometric, for example, when [intermittent clouds partially \(or fully\) cover the field-of-view](#) during an exposure. Scattered moonlight can also wreak havoc. This severely affects the accuracy of the derived photometric calibration solutions. There is one estimate of the photometric zeropoint (*magzp*) with accompanying color term (*clrcoeff*) per CCD-quadrant, where each of the 64 quadrants is calibrated independently in processing. Spatial variations in transparency at the intra-quadrant level will have led to unusable science products. The lightcurve photometry extracted from the single-exposure image products will also be suspect.

There are two flavors of science products that can be [queried from the archive](#) for which data quality flags are available for filtering: (a) single-exposure [CCD-quadrant-based files](#); and (b) [Lightcurves](#). The quality filters for each are as follows:

9.a. Quality Filtering of Single-Exposure File Products

Bad-quality or generally unusable CCD-quadrant-based images from individual epochs (including accompanying source catalog files) can be omitted when querying the archive by thresholding the **INFOBITS** value in the [archive metadata](#). If **INFOBITS** for an image has value < 33554432 (i.e., does not contain bit 25), the image and catalog data are probably usable.

The metrics and criteria used to set this "bad" data quality flag are described in Section 2.4 of the [ZSDS Advisories & Cautionary Notes](#).

Examples of image-based queries that include filtering on **INFOBITS** are given in [Section 12b.i](#) below.

9.b. Quality Filtering of Epochs in Lightcurves

Analogous to the flagging of "bad-quality" images ([Section 9a](#)), bad or generally unusable observation epochs in lightcurves can be omitted by thresholding the **catflags** column in the [lightcurve metadata](#). If **catflags** for an image has value < 32768 (i.e., does not contain bit 15), the photometry at that epoch is probably usable.

This flagging removes epochs based on their overall image/calibration quality. **catflags** also encodes possible issues at the *source level*, for example, contamination by bad pixels. These bits are defined in Section 10.6 of the [ZSDS Explanatory Supplement](#). If you demand perfectly clean extractions at every epoch, we advise specifying **catflags = 0** when querying lightcurve epochs.

Examples of lightcurve queries that include filtering on **catflags** are given in [Section 12b.iii](#) below.

10. What you should know about the ZTF Release Products

The following are high-level advisories. Visit the link in [Section 11](#) for a more detailed list.

1. DR2 contains products from both the [Public and Private Surveys](#), derived from individual exposures covering the observation spans summarized in [Section 2](#). All *i*-filter data was acquired under private survey time. All exposures in the public survey have an integration time of 30 seconds. Exposures in the private surveys have a mixture of integration times: 30, 60, 90, 120, 240, and 300 seconds, with the most common being 30 seconds.
2. The archive contains products with *basic automated* data-quality assurance applied during processing. The primary criterion for archiving a science image (along with its derived products) is that it must have passed astrometric and photometric calibration using thresholds on metrics tuned to yield *potentially usable* science products. "Bad" (unusable) data in the archive is still possible. This is data affected by clouds, low atmospheric transparency and spatial variations therein, moon contamination, bright source scattering artifacts, unmasked aircraft and artificial satellites, transient detector behavior including cross-talk, bad seeing or focus, and/or inaccurate telescope tracking. The [archive metadata](#) contains flags at both the [image-level](#) and [epoch-level within individual lightcurves](#) to identify and omit likely unusable data from queries ([see Section 9](#)).
3. Calibrated ZTF photometry can show biases of up to 0.025 mag for predominately bright sources with *g*, *r*, *i* magnitudes $< \sim 15.5$ relative to source photometry in the [Pan-STARRS1 \(PS1\) MeanObject DR1 Catalog](#). This is present in both the PSF-fit-derived and aperture-derived catalogs. These biases are field, CCD-quadrant, and magnitude dependent. The lightcurve photometry (when retrieved through either the [GUI](#), [API](#), or [tar balls](#)) includes [corrections for various biases](#), resulting in final photometric accuracies (with respect to PS1) of typically $< \sim 0.01$ mag.
4. There is no separate searchable database storing source measurements from the *single-exposure* catalog files. These measurements can only be accessed by [downloading the catalog files](#), which are in FITS-binary table format. Each table file corresponds to a single CCD-quadrant.
5. Single-exposure source photometry can be accessed at the *source-level* indirectly by retrieving entire lightcurves through either the [GUI](#), [API](#), or [tar balls](#). These products also have various photometric corrections applied (note 3 above), while the single-exposure catalog files do not include these refinements.
6. Large spatial queries using the [GUI-driven lightcurve service](#) may take longer than expected depending on user-load. An alternative for retrieving lightcurves is to submit source positions to the [lightcurve API](#). We recommend first [querying the Objects Table](#) to ensure your positions return data (however see notes 9, 10, and 11 below).
7. Lightcurves were constructed using exclusively measurements from the calibrated single-exposure PSF-fit-derived catalogs, not the aperture-based photometry catalogs.
8. The photometry catalogs, including lightcurve products, contain measurements of both point-like and extended objects. The PSF-fit photometry measurements are optimal for point-sources only. Concentric aperture photometry measurements are more optimal for extended objects.
9. Lightcurves were constructed using seed detections from the deeper (co-add) Reference Image PSF-fit catalogs. These "seed sources" were loaded into the [searchable Objects Table](#) where their photometry is ~ 2 to 2.5 magnitudes deeper than the single-exposure catalogs. Therefore, a majority of faint sources in the Objects Table (fainter than the single-exposure sensitivity limits) will not have lightcurves. Furthermore, objects with photometry hovering near the single-exposure detection limits will have incomplete temporal-coverage and therefore more sparsely sampled lightcurves.
10. Reference Images and their catalogs (loaded into the Objects Table) were generated by stacking single-exposures acquired from all [science programs \(public, private, and Caltech-time observations\)](#). These programs covered two overlapping tiling grids on the sky, a primary grid and a secondary grid, to mitigate gaps between CCDs on the focal plane. The single-exposures included in DR2 however (from which lightcurves were constructed), do not cover all survey fields from both grids. Therefore, expect to see missing lightcurves for many sources in the Object Table.
11. When [querying the Objects Table](#) to retrieve lightcurves, the *nobsrel* (and *ngoodobsrel*) metrics report the *total* (and *total unflagged*) number of lightcurve epochs included in DR2. The total number of epochs, including **unreleased** epochs from all [science programs \(public, private, and Caltech-time observations\)](#) are indicated by the *nobs* and *ngoodobs* metrics. The latter will usually exceed *nobsrel* and *ngoodobsrel*. All lightcurve-collapsed metrics in the Objects Table are computed using epochal data from all science programs.
12. **The lightcurve photometry measurements (*mag* values) already have their epoch-dependent photometric zeropoints applied (*magzp* column in returned metadata). All photometry is in the native ZTF photometric system. No color corrections are applied (or rather, zero color in**

the *AB* system is assumed). To transform photometry onto the *AB* (PS1) system, you will require knowledge of the source color in that system. The exact color used during initial photometric calibration against PS1 is defined by column *pcolor* and the color coefficient to transform to the PS1 system is given by column *clrcoeff*. The procedure for applying color corrections is described in Section 10.1.1 of the [ZSDS Explanatory Supplement](#).

13. In DR2, a difference image (file suffix **scimrefdiffimg.fits.gz*; see [Section 8a](#)) will only accompany a single-exposure science image in the archive if a Reference Image corresponding to the same field/CCD-quadrant/filter existed on/before the single-exposure image was processed. Reference Image generation continued throughout the survey and image differencing could only be triggered if a Reference Image was present. Therefore, missing difference image products are more prevalent during the early phase of the survey.
14. The units of the pixel values in all image products are in Digital Numbers (DN). Methods on how to apply the photometric calibration solutions to your own measurements using these products are outlined in Section 10 of the [ZSDS Explanatory Supplement](#).
15. The timestamps attached to the lightcurve photometry measurements (*hjd*, *mjd*, or *hmjd*) pertain to the **middle** of each exposure, i.e., with $0.5 \times \text{EXPTIME}$ added to the start observation times, where EXPTIME represents the integration time (FITS header keyword) of the corresponding exposure. The date/timestamps attached to all file-based products however (i.e., values for the FITS header keywords: OBSJD, OBSMJD, SHUTOPEN, DATE-OBS) pertain to the **start** of the exposure, not the middle.
16. Varying atmospheric transparency on the scale of an individual CCD-quadrant can have a significant impact on the quality of the *i*-filter fringe corrections. Fringe corrections were calibrated from high throughput images acquired under photometric conditions. The presence of intermittent cloud cover, depending on its spatial variation, can lead to erroneous corrections and unusable images.
17. Related to the previous point, photometry in *i*-filter in the lightcurve products have not been corrected for fringing effects. This amounts to a photometric scatter of ~ 0.02 to 0.03 magnitudes. The corresponding *i*-filter single-exposure science images however have been corrected for fringing. This inconsistency is due to scheduling of internal reprocessing to correct for fringing versus an earlier commencement date for source-matching in preparation for DR2. Future releases will ensure consistency between images and extracted *i*-filter photometry.

11. Extended (detailed) Advisories and Cautionary Notes

A more detailed compilation of advisories and known caveats specific to each data product are given in: [ZSDS Advisories & Cautionary Notes](#)

These notes are progressively updated as issues are resolved, new ones become known, or as we learn of new tips or software that could be of use to the community.

12. How to Access ZTF Data Products

Access to all ZTF data products is through the online (GUI-based) web-tools and API services of the NASA/IPAC Infrared Science Archive (IRSA) linked from: <https://irsa.ipac.caltech.edu/Missions/ztf.html>.

Below we provide links to specific GUIs and documentation describing how to access the archive products. Examples using the API services are also given.

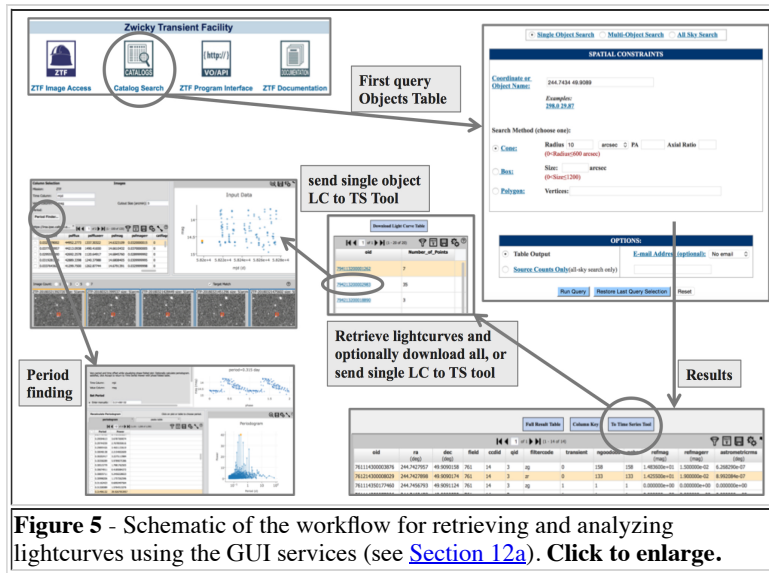
12.a. Product-specific Access GUIs and Recipes

- To visualize, analyze, and retrieve any of the [file-based products](#) (single-exposure science or reference images, and/or their catalogs or other files), use the following GUI: <https://irsa.ipac.caltech.edu/applications/ztf/>. You can supply a sky position, a list of positions, or names of objects that can be resolved, including Solar System objects or an orbital ephemeris. The query returns the CCD-quadrant images touching these positions and metadata for additional filtering. **An important metadata column you will want to filter is the INFOBITS value, primarily for "bad" quality data** (see [Section 9a above](#)). The GUI allows selected-image previews and interactive analysis. Entire file products or cutouts on specific regions can be packaged and downloaded.
- Lightcurves can be retrieved, visualized, and analyzed using the GUI services through three steps. The third step below uses the Time Series Tool to visualize and analyze an individual lightcurve.
 1. First query the DR2 Objects Table containing sources extracted from Reference Images (co-added single-exposures): [ZTF DR2 Objects](#). You can perform a spatial cone-search, box or polygon search, supply a list of search positions, as well as include filtering on any of the pre-computed lightcurve-collapsed metrics shown in the form. This query returns a list of the objects for which lightcurves *potentially exist* (subject to [advisories 9, 10, 11 in Section 10](#)). This list can be saved to a file and fed to the [lightcurve API](#), or the results can be sent directly to the Time Series Tool (see next step).
 2. On the results page following the query in step 1, click on "To Time Series Tool" to retrieve the lightcurve(s) of your object(s). At this stage, you can click "Download Light Curve Table" to save the lightcurves for all objects to a single ASCII table, concatenated and distinguished by object ID (*oid*). **Metadata is also written, which includes the *catflags* column for identifying and filtering bad observation epochs** (see [Section 9b above](#)).
 3. Alternatively, given the list of object IDs that have lightcurve data in step 2, you can click on an individual object and send its lightcurve to the Time Series Tool. **This tool allows interactive filtering on the lightcurve metadata (for example, omitting bad observation epochs by filtering the *catflags* value)**. This tool provides a visualization of the single-exposure images for neighboring lightcurve epochs, allows you to compute a periodogram and a period therefrom, and then plot a phase-folded lightcurve. There is also an option to supply your own period for the phase-folding.

[Figure 5](#) shows a schematic of this workflow.

- A custom tool for recovering and characterizing *known* Solar System Objects (SSOs) in ZTF data is the Moving Object Search Tool (MOST): <https://irsa.ipac.caltech.edu/applications/MOST/>. This is a *precovery* tool where you can specify a known SSO name, [NAIF ID](#),

ephemeris, or orbital elements, and the observation time range. The service returns the single-exposure science image filenames containing the SSO, associated archive metadata, orbit plots, refined ephemeris, and more orbital parameters. Images or cutouts (and/or associated photometry catalogs) can then be retrieved using the [image-download API](#). For more information, see the [full usage instructions for the MOST GUI](#). An [API for the MOST tool](#) is also available.



12.b. Example Queries using the APIs

Application Programming Interfaces (APIs) accompany most of the GUI data-retrieval services. These APIs can be executed from within your own software to enable repetitive and/or bulk data downloads.

An overview for retrieving **file-based** products using APIs is given on the [Image/Catalog API Page](#). API queries can include thresholding on any of the [available archive image metadata](#) parameters.

Examples of using APIs to retrieve file-based products and lightcurves are given below.

i. Querying Single-Exposure Science Image Products using the API

To retrieve [file-based single-exposure science image products](#) that touch a fixed R.A.,Dec position, fall within an observation JD range, and [are likely to be of "good" \(usable\) quality with INFOBITS < 33554432](#) (see [Section 9a](#)), first query their metadata using the *wget* utility, e.g.,

```
wget "https://irsa.ipac.caltech.edu/ibe/search/ztf/products/sci?
POS=255.9302,11.8654&WHERE=obsjd>2458219.9678+AND+obsjd<2458228.8155+
AND+infobits<33554432" -O out.tbl
```

where all inputs reside on one line. Then use the output metadata table (out.tbl) contents to construct the image URL-paths/ilenames. Using the metadata column names, a science-image will have the generic URL-path/filename:

```
https://irsa.ipac.caltech.edu/ibe/data/ztf/products/sci/
YYYY/MMDD/fracday/ztf_filefracday_000field_filtercode_
cccdid_imgtypecode_qqid_sciimg.fits
```

where identifiers in **bold green** are the values of actual columns in the out.tbl table, and YYYY (year), MM (month), DD (day), and *fracday* (fractional time of day) can be extracted from **filefracday**. These images can then be retrieved using the *wget* utility. For the example above, the first metadata record in out.tbl would be retrieved using:

```
wget https://irsa.ipac.caltech.edu/ibe/data/ztf/products/sci/
2018/0411/467847/ztf_20180411467847_000535_zr_c11_o_q3_sciimg.fits
```

Any of the accompanying products can be retrieved by replacing *sciimg.fits* with another filename suffix (see [Section 8a](#)). Instead of retrieving the entire image, you can download a square cutout centered at a specific R.A.,Dec and specific size, and save the output to a file (optionally gzipped). For the example above:

```
wget "https://irsa.ipac.caltech.edu/ibe/data/ztf/products/sci/
2018/0411/467847/ztf_20180411467847_000535_zr_c11_o_q3_sciimg.fits?
center=255.8535,12.0503&size=60arcsec&gzip=false" -O cutout.fits
```

If the API fails to return a file (or its metadata), you can try [navigating the archive tree directly](#) to search for the specific product:

<https://irsa.ipac.caltech.edu/ibe/data/ztf/products/sci/>. For guidance, listings of the DR2 [single-exposure Science](#) products are given in [Section 8a](#). A description of the path and filename identifiers is given in Section 7 of the [ZSDS Explanatory Supplement](#).

ii. Querying Reference Image Products using the API

To retrieve [file-based Reference Image products](#) that touch a fixed R.A.,Dec position in only the *r*-filter (*fid*=2), first query their metadata using the *wget* utility, e.g.,

```
wget "https://irsa.ipac.caltech.edu/ibe/search/ztf/products/ref?
POS=358,25.6&WHERE=fid=2" -O out.tbl
```

where all inputs reside on one line. Then use the output metadata table (out.tbl) contents to construct the image URL-paths/filenames. Using the metadata column names, a Reference Image will have the generic URL-path/filename:

```
https://irsa.ipac.caltech.edu/ibe/data/ztf/products/ref/
prefield/fieldfield/filtercode/ccdccdid/qqid/
ztf_field_filtercode_ccdid_qid_refimg.fits
```

where identifiers in **bold green** are the values of actual columns in the out.tbl table, and *prefield* is the first three (left-zero-padded) digits of the six-digit **field** value. These images can then be retrieved using the *wget* utility. For the example above, the first metadata record in out.tbl would be retrieved using:

```
wget https://irsa.ipac.caltech.edu/ibe/data/ztf/products/ref/
001/field001596/zr/ccd16/q2/ztf_001596_zr_c16_q2_refimg.fits
```

Any of the accompanying products can be retrieved by replacing *refimg.fits* with another filename suffix (see [Section 8b](#)). Instead of retrieving the entire image, you can download a square cutout centered at a specific R.A.,Dec and specific size, and save the output to a file (optionally gzipped). For the example above:

```
wget "https://irsa.ipac.caltech.edu/ibe/data/ztf/products/ref/
001/field001596/zr/ccd16/q2/ztf_001596_zr_c16_q2_refimg.fits?
center=357.46871,26.00549&size=100arcsec&gzip=false" -O cutout.fits
```

If the API fails to return a file (or its metadata), you can try [navigating the archive tree directly](#) to search for the specific product:

<https://irsa.ipac.caltech.edu/ibe/data/ztf/products/ref/>. For guidance, listings of the DR2 [Reference Image](#) products are given in [Section 8b](#). A description of the path and filename identifiers is given in Section 7 of the [ZSDS Explanatory Supplement](#).

iii. Querying Lightcurves using the API

The API functionality corresponding to the [GUI-driven recipe for retrieving lightcurves](#) is described on the [Lightcurve Programming Interface Page](#). Numerous examples are given on this page. Below we provide a more generic example that includes most parameters of interest. **You will always want to exclude observation epochs associated with bad/unusable data by masking *catflags* values equal to 32768, -- the "cloud-affected and/or moon-contamination" flag (decimal bit 15); see [Section 9b](#).** Alternatively, you can exclude epochs with any non-zero bit by using the *catflags* mask value 65535 in the query below.

The following query returns a concatenated list of lightcurves for objects falling within a 10 arcsec (~0.0028°) radius from position R.A.,Dec = 255.9302°, 11.8654° in the *r*-filter, where each has ≥ 3 epochs that fall within the MJD range 58194.0...58483.0 and all consist of only "good" (likely usable) measurements. Lightcurves are stored in the output ASCII table: out.tbl. The concatenated lightcurves are distinguished by their ObjectIDs therein (column *oid*).

```
wget "https://irsa.ipac.caltech.edu/cgi-bin/ZTF/nph_light_curves?
POS=CIRCLE+255.9302+11.8654+0.0028&BANDNAME=r&NOBS_MIN=3&
TIME=58194.0+58483.0&BAD_CATFLAGS_MASK=32768&FORMAT=ipac_table" -O out.tbl
```

All inputs reside on one line. A lightcurve (with common *oid* values) is represented by columns *mag ± magerr* versus *mjd* or *hjd*. The out.tbl also contains metadata to reconstruct the single-exposure science image path/file names that you can later download using the *wget* utility, or alternatively, cutouts on your position of interest (see [Section 12b.i](#)).

You can also upload the out.tbl file from above to the [Time Series Tool](#) to enable visualization, analysis, and period finding, analogous to the [GUI-driven method described in Section 12a](#). Ensure you select "ztf" from the menu before uploading. Following your upload, ensure only one ObjectID (*oid*) is selected for visualizing, using the filter () icon in the Time Series Tool.

iv. Solar System Object Preccovery using the API

The API equivalent of the [Moving Object Search Tool](#) (GUI) is described on the [MOST Programming Interface Page](#). For example, to retrieve all single-exposure science images containing [Asteroid 438973 Masci](#), first query their metadata using the *wget* utility:

```
wget "https://irsa.ipac.caltech.edu/cgi-bin/MOST/nph-most?
catalog=ztf&input_type=name_input&obj_name=Masci&
obs_begin=2018+03+17&obs_end=2018+12+31&output_mode=Brief" -O out.tbl
```

where all inputs reside on one line. Then use the output metadata table (out.tbl) contents to construct the science image URL-paths/filenames (see

[Section 12b.i above](#)). These images can then be downloaded using the *wget* utility. Alternatively, cutouts centered on the object's R.A.,Dec in each image, as listed in out.tbl, can be downloaded.

12.c. Bulk Download of all Lightcurves

The lightcurves included in this release have been packaged into gzipped tar files. A selection of basic (most necessary) metadata accompany each lightcurve, primarily IDs to enable the retrieval of associated metadata from the archive, for example, images or Object Table metrics using the access methods above.

The following URL contains a listing of the tar-gzipped filenames and their (compressed) sizes:

https://irsa.ipac.caltech.edu/data/ZTF/lc_dr2/

When uncompressed, their total volume is ~ 3.4 TB. You can click on individual files to download them, or use the *wget* utility to automate the downloads. If your operating system does not automatically unzip these, you can use *gunzip file.tar.gz* followed by *tar -xvf file.tar* to unpack. A list of corresponding MD5 checksums is also provided for those who want to verify file contents following a download. On a Unix/Linux OS, the files can be verified using *md5sum -c checksums.md5*.

The files are labelled by survey-Field ID where each Field spans $\approx 7^\circ \times 7^\circ$. Each filename also includes the minimum to maximum RA and Dec values spanned by all the objects contained therein. These RA, Dec ranges can be used to identify the sky region(s) of interest in case you are interested in downloading a subset. The DR2 lightcurves are spread across 856 fields.

Each file unpacks into an ASCII table with the following structure:

```
# ObjectID (oid), nDR2epochs, FilterID, FieldID, RcID, ObjRA, ObjDec
HMJD, mag, magerr, clrcoeff, catflags
...
Click for example \(truncated\)
```

The lightcurves are delimited by lines: "# Object / lightcurve metadata ...". Following this line is the actual lightcurve for that object. The columns are as follows:

ObjectID: Unique Object Identifier. This is the *oid* that is returned by [queries on the Objects Database Table](#). This ID can be used to retrieve additional metadata for an Object or lightcurve.

nDR2epochs: The number of observation epochs in the lightcurve for this object, included in this data release only.

FilterID: Filter for the lightcurve photometry: 1 => *g*; 2 => *r*; 3 => *i*.

FieldID: The survey Field Identifier. Lightcurves in DR2 are spread across 856 Fields. This identifier can be used to retrieve additional archive metadata.

RcID: The readout-channel Identifier (or CCD-Quadrant index) that contains the object. The RcID runs from 0 to 63 over the [ZTF focal plane](#). In combination with FieldID, this can be used to retrieve additional archive metadata.

ObjRA: Object Right Ascension from the input [Reference Image \(seed\) catalog](#) corresponding to the FieldID, RcID, and FilterID [decimal degrees].

ObjDec: Object Declination from the input [Reference Image \(seed\) catalog](#) corresponding to the FieldID, RcID, and FilterID [decimal degrees].

HMJD: Heliocentric-based Modified Julian Date [days] corresponding to the **middle of each exposure** and approximate position of the object. The HMJD is derived from "HJD - 2400000.5" where HJD is the Heliocentric Julian Date.

mag: Calibrated magnitude for a source with color $g - r = 0$ in the AB photometric system. See [Cautionary Note #12 in Section 10](#).

magerr: Corresponding 1- σ uncertainty in *mag* estimate; excludes the (usually small) uncertainty associated with the calibration zeropoint and possible systematics relative to external photometry catalogs (for example [PS1](#)).

clrcoeff: Linear color coefficient term from photometric calibration that can be applied to the *mag* estimate if you know the AB $g - r$ color of your source. See [Cautionary Note #12 in Section 10](#).

catflags: Photometric/image quality flags encoded as bits ([Section 9b](#)). In particular, **you will always want to exclude observation epochs affected by clouds and/or the moon. These epochs have catflags = 32768 (decimal bit 15).**

A utility to extract and parse the lightcurves in the unpacked ASCII tables is called [zort](#). This tool enables custom filtering, the identification of lightcurves belonging to the same object across different filterIDs, and plotting.

13. Help Desks

For any archive or data-access related issues, which includes anomalies with any of the GUI tools or APIs for data retrieval and analysis, please email: irsasupport@ipac.caltech.edu

For questions related to data-quality, format, content, processing algorithms, or product usage, including documentation, please email: ztfdatasystem@gmail.com

14. Further Documentation & Relevant Publications

A detailed description of the processing pipelines, data products (including alert packets), instructions for product retrieval, filename identifiers, data formats, and product usage can be found in:

[The ZSDS Explanatory Supplement: Pipelines, Definitions, Data Products & Access](#)

Two relevant publications from the special [ZTF Focus Issue of PASP](#):

- An overview of the ZTF Science Data System:
[*The Zwicky Transient Facility: Data Processing, Products, and Archive, 2019, vol 131 \(issue 995\), 18003*](#)
- An overview of the technical specifications of the camera and observing system, its performance, and ZTF survey design:
[*The Zwicky Transient Facility: System Overview, Performance, and First Results, 2019, PASP, vol 131 \(issue 995\), 18002*](#)

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