ATLAS PDS Bundle Overview

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1 Introduction

This document describes in detail the archival holdings from the Asteroid Terrestrial-impact Last Alert System (ATLAS) survey in NASA's Planetary Data Systems (PDS). ATLAS is a global, all-sky wide-field survey operated by the University of Hawai'i that searches continuously for hazardous near-Earth objects (NEOs). Images and source catalogs from the ATLAS survey are of use to astronomers beyond Solar System science, and ATLAS and NASA/PDS have coordinated storage of ATLAS images and source catalogs within PDS so that they can be exploited by the wider astronomical community.

Readers of this document should have a working knowledge of astronomical imaging using charge-coupled devices (CCDs) and the Flexible Image Transport System (FITS) file format[1]. The ATLAS system design is described in great detail in [2], and a high-level overview of ATLAS data processing can be found in the *ATLAS Operations and Data Processing* document that accompanies this one. For more information about near-Earth asteroids and planetary defense, we invite readers to consult the NASA Planetary Defense Coordinate Office[3], the IAU Minor Planet Center[4], and the NASA/Jet Propulsion Laboratory Center for Near Earth Object Studies (CNEOS)[5].

2 ATLAS PDS Bundle

The ATLAS data at PDS are organized into *bundles* that correspond to a lunar "observing cycle" number (or OC number), a convention adopted from the Pan-STARRS survey. An observing cycle represents a full moon-to-full moon interval that forms convenient boundaries for survey telescope operations. While the robotic ATLAS survey does not institute regularly scheduled downtime for maintenance, other survey telescopes use time near the full moon when the sky is bright and discovery yields are lower to shut down operations for several days for maintenance or to reduce operational costs. The ATLAS observing cycle number is defined as

$$OC = int((NN - 51564)/29.53058867)$$

where 51564 is the night number for the first full moon in the year 2000, and 29.53058867 days is the synodic period of the Moon's orbit around the Earth, i.e. the average time between full moons. Observing cycle zero starts on night number 51564, or January 21, 2000. The first ATLAS survey observations start with observing cycle 190, June 4, 2015.

Within each ATLAS PDS bundle are *collections* corresponding to ATLAS night numbers. The ATLAS night number is a local concept provides a single integer number based on a modified Julian date (MJD) that represents a noon-to-noon interval under which all observations for a single night occur[1]. Each night within an observing cycle is an independent collection, and data from all ATLAS telescopes with the night number constitute the collection. Within the ATLAS pipeline, data are organized around the notion of an *observation* — an exposure taken by an ATLAS telescope at a particular time and pointed at a particular location on the sky. A single observation initiates processing within the ATLAS pipeline that calibrates the image and searches the image for astronomical sources. Each observation is given a name unique across the ATLAS dataset and can be used to quickly identify the ATLAS telescope that executed the observation, the modified Julian date (MJD) of the observation, and passband. The structure of an ATLAS observation name is described in Table 2.

An ATLAS observation therefore corresponds to a PDS *product*. Many data files are produced as a result of data processing for a single ATLAS observation, but only products deemed useful to users of ATLAS data have been selected for archiving within PDS. An ATLAS collection in PDS will typically consist of several thousand products, depending on which telescopes were observing on the night corresponding to the collection. A diagram illustrating the organization of ATLAS bundles is shown in Fig. 1.

An observation by any of the four ATLAS telescopes is given a globally unique name, associated with a night number, that is used in a prefix for all data products related to that exposure. The night number is a local concept, since it represents a local noon-to-noon interval during which observations can be taken. The

[1] More precisely, the night number is the integer component of the floating-point Modified Julian Date at a time just after the local midnight.

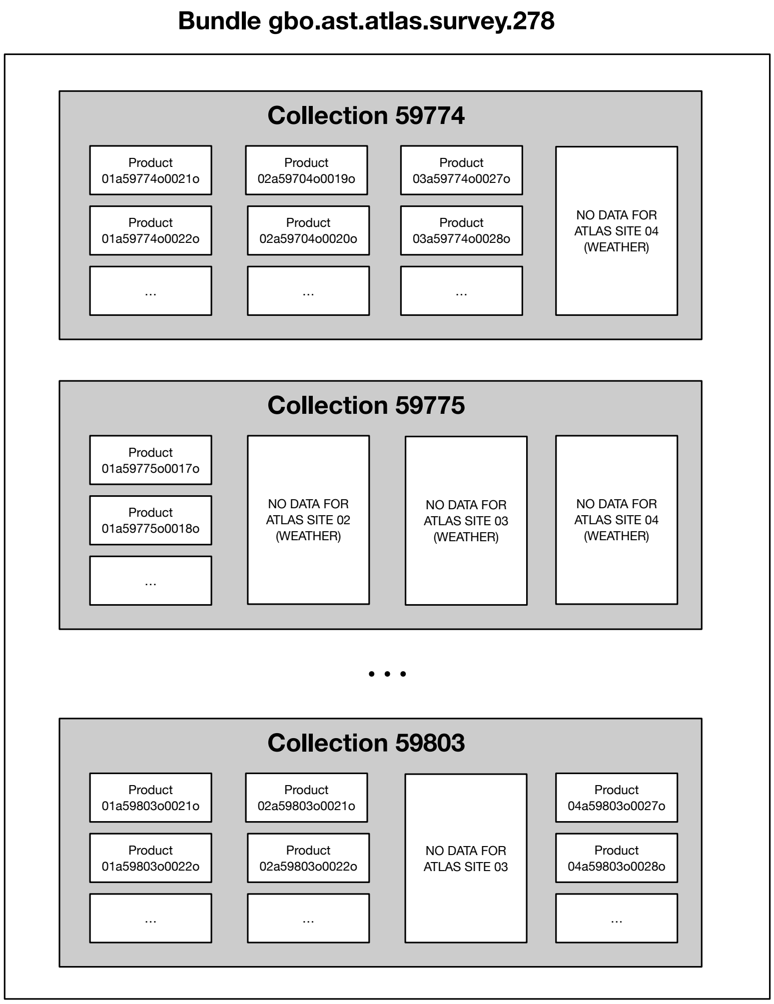

Figure 1: ATLAS bundle structure. Bundles are organized by lunar observing cycle ("OC number"), then into collections by night number, then into products by ATLAS exposure number.

night moves from east to west, starting with South Africa, and ending with Hawai'i. The ATLAS observation name structure is shown in Table 2.

01a59201o0019c	
01	ATLAS site (01=Maunaloa, 02=Haleakala, 03=South Africa, 04=Chile)
a	Aperture identifier (a=acam, x=xcam, k=allsky)
01a	“Sitecam”, combination of site and camera identifier
59201	Night number based on Modified Julian Day (e.g. Fri Dec 18 2020 UTC)
o	Exposure type (o=object, f=skyflat, s=focus, e=engineering)
0019	Per-telescope, per-night sequence number
c	Filter (c=cyan, o=orange; see main text regarding other filters)

Table 1: ATLAS observation name schema

Note that only ATLAS “acam” exposures are currently archived to PDS. “acam” is the internal name for the main imager on an ATLAS telescope. In the future, data products from the auxiliary “xcam” and the all-sky camera (whose nighttime images are photometered for stars) may be archived. Only the science exposures, *i.e.* those with a FITS OBJECT header, are archived at PDS. The ATLAS telescopes have additional passband filters installed besides the ATLAS-standard c and o filters, but these have limited utility for the ATLAS NEO mission and are currently only used for experimental purposes; they may be used for production observations in future. Those filters are: g=SDSS g[6], r=SDSS r, i=SDSS i, z=SDSS z, u=SDSS u, B=Johnson B[7], V=Johnson V, R=Johnson/Cousins R, I=Johnson/Cousins I, H=H-Alpha, O=O[III].

3 Terminology

For clarity, the following terms are used within the ATLAS Project but may be referred to by a different name in other projects:

- Reduced image — A calibrated, cleaned or “detrended” image, corrected to have instrumental artifacts quantified and removed.
- Wallpaper — Often called a “template” or “static sky” image, this is a pixel-aligned image of the nonvarying sky at the same telescope pointing for a reduced image.
- Diff image — The resulting image when the wallpaper image is subtracted from a reduced image. This image contains astronomical sources that have changed or moved compared to the wallpaper.

4 Bundle and Collection Files

The following table illustrates the collection of files that are created for a given observation. In this example, the exposure is named “02a59613o0385c”:

Product	Format	Description
ATLAS_bundle_overview.xml	XML	Bundle XML Label

File	Description	Format
02a59613o0385c.fits	Reduced image	FITS
02a59613o0385c.fits.xml	Reduced image label	XML
02a59613o0385c.fits.fz	Reduced image (compressed)	FITS FPACK
02a59613o0385c.dph.csv	Reduced image detection catalog	CSV
02a59613o0385c.dph.csv.xml	Reduced image detection catalog label	XML
02a59613o0385c.diff	Diff (subtracted) image	FITS
02a59613o0385c.diff.xml	Diff (subtracted) image label	XML
02a59613o0385c.diff.fz	Diff (subtracted) image (compressed)	FITS FPACK
02a59613o0385c.ddc.csv	Diff (subtracted) detection catalog	CSV
02a59613o0385c.ddc.csv.xml	Diff (subtracted) detection catalog label	XML

Table 2: An example set of files from a single telescope exposure named "02a59613o0385c" from the 59613 collection within the ATLAS PDS bundle.

5 ATLAS Reduced Data Products

5.1 Overview

The reduced data products consist of the reduced image compressed with FPACK[2], the image's corresponding deep source catalog, and a user-friendly bin-by-8 "thumbnail" JPEG image.

Product	Format	Description	Pipeline?
OBS.fits.fz	FITS FPACK	Multi-extension FITS reduced image	Y
OBS.fits.xml	XML	Reduced image label	N
OBS.dph.csv	CSV	Catalog of reduced image detections	Y
OBS.dph.csv.xml	XML	Reduced image detection catalog label	N
OBS.jpg	JPEG	1/8 scale reduced image	Y

Table 3: Listing of reduced image files for an ATLAS observation. Files with "N" in the Pipeline? column are not produced by the reduction pipeline but are generated specifically for the ATLAS PDS export.

5.2 Reduced Image

An ATLAS reduced image is a multi-extension FITS (MEF) file with the following image plane extensions:

Extension #	Name	Description
1	image	Reduced (calibrated) image
2	mask	16-bit mask (see mask bit definitions in Table 5)
3	variance	bin-by-8 net variance
4	eadu	bin-by-8 (inverse) gain, electrons per analog-to-digital unit (ADU)
5	dark	bin-by-8 dark (subtracted from raw image)
6	sky	bin-by-8 sky (subtracted from raw image)
7	cloud	bin-by-8 cloud (correction for cloud extinction)
8	binim	bin-by-8 reduced image
9	col_bias	column (parallel overclock) bias levels for each CCD amplifier
10	row_bias	row (serial overclock) bias levels for each CCD amplifier

Table 4: Description of the 10 FITS extensions present in an ATLAS reduced image.

[2] ATLAS fpacked images use the default Rice compression

The reduced image and variance planes are computed according to the following formulae:

$$RED = 1/cloud \times (1/FLAT \times (RAW - col\_bias - row\_bias - D \times DARK) - sky) + S$$

$$var = (RNADU^2 + D \times DARK/G)/(FLAT \times cloud)^2 + sky/(G \times FLAT \times cloud^2)$$

where

- RAW = full resolution input image
- col_bias = full resolution column bias array
- row_bias = full resolution row bias array
- DARK = full resolution reference dark array
- D = dark image scaling factor
- FLAT = full resolution flatfield, unity normalized
- G = nominal inverse gain (EADU=GAIN)
- S = nominal sky level (BCKGND)
- cloud = binned cloud transmission
- sky = binned sky level, nominally equal to S
- RN ADU = CCD read noise in ADU
- N = image binning factor for variance, eadu, dark, sky and cloud images

It is assumed that the variance, eadu, dark, sky, and cloud images do not have any high frequency spatial variation, so a binned version provides suitable resolution. The bin factor N is found in the header as "AUXBIN". To obtain nominal variance, not including stars or other objects, just use the "VARIANCE" extension. To obtain pixel-by-pixel variance, including objects, add $[(PixVal(x,y) - S)/eadu(x/N, y/N)]$ to the variance image. Note that cleaned image is saved with a "SKY" bias S left in place; this value can be found in the header as "BCKGND".

If there is no obvious variation in the sky background the 'sky' extension is uniformly set to the value S ("BCKGND"). If there is no obvious cloud extinction the "CLOUD" extension is uniformly 1. If the image is corrected for cloud extinction the light loss is found in the "CLOUD" extension, and the "eadu", "variance" and "sky" extensions are adjusted appropriately.

The col_bias and row_bias extensions have 4 rows or columns for each amplifier. The first is the median bias value, either derived from parallel (col_bias) or serial (row_bias) overclocks. The second is the RMS, judged from the quartiles. The third is the smoothed version that has been subtracted from the image, and the last is the variance of that. These two extensions should be present if it is desirable to be able to reproduce a raw image from a flattened one; they are not used by any of the subsequent processing, however.

The astrometric component of the reduction writes the FITS CRPIX/CRVAL pointing information and 3rd-order polynomial SIP[8] and PV[9] distortion terms in the FITS headers[8].

The mask plane is a 16-bit image where the bits have the following meaning:

BIT NAME	Hexadecimal Value	Meaning
MASK_BAD	0x0001	Bad pixel (known dark defect on CCD)
MASK_SAT	0x0002	Saturated pixel (too bright)
MASK_CTE	0x0004	Bad parallel charge transfer
MASK_OBSC	0x0008	Obscured pixel
MASK_EDGE	0x0010	Edge pixel
MASK_XTALK	0x0020	Amplifier cross-talk contaminated pixel
MASK_BRIGHT	0x0040	Known bright defect on CCD
MASK_BLEED	0x0080	Bright star bleed pixel
MASK_CR	0x0100	Cosmic ray pixel
MASK_HALO	0x0200	Bright star halo pixel
MASK_GHOST	0x0400	Optical ghost pixel
MASK_HIDE	0x0800	Hide this pixel in JPEG images
MASK_SUSPECT	0x8000	Poor/nonlinear pixel

Table 5: Mask bitplane definitions. These values should be considered advisory and indicate pixels in the reduced image the downstream consumers should treat with caution or omit altogether.

5.3 Reduced Catalog

The reduced deep source catalog is produced as a post-processing step in the general reduction process, using `dophot`[10] to find all star-like sources to a 5-sigma cutoff. It assumes that the basic reduction has succeeded with a high enough image quality that stellar point spread functions (PSFs) can be well-characterized across the image; if this is not true, there may not be a reduced source catalog for a given exposure.

The output catalog is a tabular file with extension '.dph' (for `dophot`) converted to CSV for PDS with the following columns:

Column #	Name	Description	Units
1	RA	Right ascension of weighted detection centroid (J2000)	degrees
2	Dec	Declination of weighted detection centroid (J2000)	degrees
3	m	Apparent magnitude	AB magnitudes
4	idx	Dophot object index	integer
5	Type	Dophot source type (1,2,3 are good, 4+ are failures)	integer
6	xtsk	X center of weighted source centroid (ATLAS `tphot` convention)	pixels
7	ytsk	Y center of weighted source centroid (ATLAS `tphot` convention)	pixels
8	minst	Instrumental magnitude	mag
9	dminst	Uncertainty in m and fitmag	AB magnitudes
10	sky	Sky value of the Waussian fit	ADU
11	major	PSF major axis FWHM	pixels
12	minor	PSF minor axis FWHM	pixels
13	phi	Angle of major axis, counterclockwise from x-axis	degrees
14	probgal	Dophot extendedness parameter	$-\infty$ to $+\infty$
15	apmag	Aperture magnitude for bright stars	mag
16	dapmag	Uncertainty in aperture magnitude	AB magnitudes
17	apsky	Aperture sky value	ADU
18	ap-fit	Aperture magnitude – fit magnitude	AB magnitudes

Table 6: Description of dophot table values that make up the reduced image catalog. "ADU" here means analog-to-digital units.

6 ATLAS Diff Data Products

6.1 Overview

Image subtraction ("diffing") is the second part of the ATLAS pipeline, the stage that examines a reduced image for things that have changed with respect to a static sky image (the "wallpaper"). The diff stage assumes that the reduction has succeeded in flattening the image and has produced a good WCS solution. It generates a template image from the deep wallpaper, runs `atpants` (derived from `hotpants`[11]) to make the difference image, uses `tphot` to find any transient or moving objects in the observation, and then attempts to classify the detections. The outputs are a single-extension FITS image file containing the subtracted image (the .diff.fz file) and a separate table of classified diff detections (.ddc).

Not all reduced images will have a matching set of diff products. Images that are vignetted, badly out of focus, contaminated by bright clouds, or have a shutter actuation or telescope tracking problem may be too poor to produce PSF and sky information needed for a subtraction.

Product	Format	Description	Pipeline?
02a59613o0385c.diff.fz	FITS FPACK	Diff image label	Y
02a59613o0385c.diff.xml	XML	Diff image label	N
02a59613o0385c.ddc.csv	CSV	Diff detection catalog	Y
02a59613o0385c.ddc.csv.xml	XML	Diff detection catalog label	N

Table 7: Listing of diff image files for an ATLAS observation. Files with "N" in the Pipeline column are not produced by the subtraction pipeline but are generated specifically for the ATLAS PDS export.

6.2 Diff Image

The subtracted image (or "diff" image) from an ATLAS exposure is a single-extension FITS file with file extension `.diff.fz`.

6.3 Diff Catalog

The .ddc diff detection catalog is a table of detections found in the diff image by the `imdiff_det.sh` ATLAS pipeline component. Where the reduced image employs `dophot` for its source finding, the diff images use the `tphot`[12] source finding program, which produces excellent results with subtracted images and trailed sources. `tphot` finds astronomical sources using a variety of PSF-fitting strategies, broadly called *fixed*, *free*, *trailed* and *streaked*. This capability is especially important for Solar System work, because asteroids and comets may be trailed or otherwise extended in a single 30-second ATLAS exposure.

The detections from `imdiff_det.sh` are curated by a detection classifier called `vartest` that attempts to label whether a given diff source detection is a moving object, stationary transient, or artifact based on the local pixel environment and what type of PSF was fitted. The inputs to `vartest` are the raw diff catalog from `imdiff_det.sh`, and the diff and reduced images, and a pipeline-generated file of bright stars in the image. Using all of this information, `vartest` decides whether a detection is likely to be a variable star, transient detection, cosmic ray, an image artifact such as bad pixel column or electronic crosstalk between amplifiers, or "scar" from a noisy star subtraction.

Det Class	PSF Fit Type	Description
0	Fixed	Strict fit to stellar PSF profile from same image
1	Free	Flexible fit PSF allowing some PSF parameters to vary (major, minor, phi)
2	Trailed	Fit an elongated PSF (a Waussian) compatible with a moving object
3	Streaked	Fit a very elongated ("streaked") PSF compatible with a fast-moving object
4	(unused)	(unused)
5	Negative	Fit a negative-going PSF compared to the wallpaper

Table 8: Diff detection class identifiers produced by the `vartest` classification program.

The `vartest` classifications are represented probabilistically, using a convention that $P = 0$ represents zero probability and $P = 999$ represents unity. The classifications corresponding to real astrophysical objects are: known asteroids (PKAST or Pkn), unknown asteroids or transients (PTRANS or Ptr), and variable stars (PVAR or Pvr). Objects with nonzero values of PTRANS are also assigned a probability of being a fast-moving (i.e., trailed) detection (PMOVE or Pmv). The categories of spurious detections are noise (PNOISE or Pno), electronic column artifact or "burn" (PBURN or Pbn), cosmic ray (PCOSMIC or Pcr), electronic crosstalk (PXTALK or Pxt), and star subtraction residual or "star scar" (PSCAR or Psc). The `vartest` probability classes are not exclusive — some classes are subsets of other classes, e.g. Pmov (moving) is a subset of Ptr (transient).

`tphot` is able to measure *negative* flux excursions against the background wallpaper. This can happen when there is a long-period variable star in the wallpaper that is not as bright in the reduced image as it is in the wallpaper. These measurements come "for free" from tphot and are included because they may be useful in research of stationary phenomena beyond the Solar System.

The negative excursions measured by `tphot` are represented conventionally with a nonphysical "negative magnitude" — these values should be interpreted as a source whose brightness is the absolute value of the DDC-reported magnitude; the negative sign simply indicates that the source is *fainter* than its wallpaper source. As an example, consider a source whose DDC magnitude is −17.5; this means that a source was detected in the diff image with apparent magnitude 17.5 but that the source has a brighter match in the wallpaper. The WPflux column can be used to confirm that this measurement corresponds to a true change in brightness of a wallpaper source and not a spurious noise fluctuation.

Because the `tphot` diff source finder performs fits using different PSF models, it can produce multiple measurements very close to a given location from the different PSF fits. An example would be a fast-moving trailed asteroid that has some noise in the trail; in this case, a fixed PSF fit based on stellar PSFs might produce a position off the center of the trail, but a free or trailed PSF fit would be allowed to more closely match the trailed PSF, producing a better position. When this occurs, `vartest` treats these detections that are very close to each other as a group, and `vartest` provides guidance regarding the "best" detection and which ones should be rejected as poorly-measured duplicates of the best detection. Generally, `vartest` prefers a "faster" measurement (trailed or streaked) to a slower one (fixed or free), since a streak or trail fit to a truly enlongated detection will produce a more accurate position that a stellar (fixed or free) fit.

Dup Class Code	Description
0	There were no duplicates to consider, so keep this measurement
1	All the duplicates were "slow" (free or fixed) and this one was selected
2	All the duplicates were "fast" (trailed or streaked) and this one was selected
3	There were both slow and fast duplicate detections, and this one was selected
−1	All the duplicates were "slow" (free or fixed) and this one was rejected
−2	All the duplicates were "fast" (trailed or streaked) and this one was rejected
−3	There were both slow and fast duplicate detections, and this one was rejected

Table 9: Duplicate detection codes produced by the `vartest` classification program.

Finally, Table 10 lists the columns of a DDC file.

Column #	Name	Description	Units
1	RA	Right ascension of detection (J2000)	degrees
2	Dec	Declination of detection (J2000)	degrees
3	mag	Apparent magnitude; negative is conventional and means a negative excursion	AB magnitudes
4	dmag	Apparent magnitude uncertainty	AB magnitudes
5	x	X position of detection	pixels
6	y	Y position of detection	pixels
7	major	Major axis FWHM	pixels
8	minor	Minor axis FWHM	pixels
9	phi	Orientation of major axis, counterclockwise from x-axis	degrees
10	Det	Detection class, see Table 8	0,1,2,3,5
11	chi/N	χ^2/N of the detection fit	NA
12	Pvr	Probability detection is a stationary long-persistence variable	0...999
13	Ptr	Probability detection is a short persistence transient	0...999
14	Pmv	Probability detection is moving	0...999
15	Pkn	Probability detection is a known asteroid	0...999
16	Pno	Probability detection is a noise artifact	0...999
17	Pbn	Probability detection is a CCD burn artifact	0...999
18	Pcr	Probability detection is a cosmic ray	0...999
19	Pxt	Probability detection is an electronic crosstalk artifact	0...999
20	Psc	Probability detection is a subtraction artifact near a bright star	0...999
21	Dup	Duplicate detection code, see Table 9	−3...3
22	WPflux	Flux in wallpaper, scale to image	ADU
23	dflux	Uncertainty in wallpaper flux	ADU

Table 10: Diff detection catalog (DDC) table definitions.

Some of the columns in the DDC table support an error value indicating an out-of-range computed value that should not be trusted. For floating-point values, this number is precisely -99.999, and for integer values the error value is -99. Note that the vartest class probabilities encode a floating-point 0-1 probability as an integer from 0 to 999 inclusive.

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