

Lowell Uncalibrated/Calibrated Data Product Software Interface Specification for Data Collected in Support of DART Mission

Version 2.0



Technical Content Approval

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Revision Log

Rev	By	Description	Date
-	N. Moskovitz	Initial Release	10/29/2020
	R. Espiritu	Added sections for PDS and data format table. Updated naming convention for each data product	01/04/2021
	R. Espiritu	Incorporated initial PDS feedback prior to formal PDS Review	6/20/2021
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	N. Moskovitz	Added text describing discrepancy between number of raw and calibrated images, and small number of PNGs with offset reference stars	9/25/2023

1 Purpose and Scope

The data products described by the Software Interface Specification (SIS) are the Lowell uncalibrated and calibrated data products. Nick Moskovitz from Lowell Observatory produces these data products and distributes them to the DART SOC for redistribution to the DART Investigation Team and the Planetary Data System (PDS).

The purpose of this document is to provide users of the data products with a detailed description of the product and a description of how it was generated, including data sources and destinations. The document is intended to provide enough information to enable users to read and understand the data products. The users for whom this document is intended are the scientists who will analyze the data, including those associated with the DART mission and those in the general planetary science community.

1.1 DART Mission Purpose and Goals

DART is a low-cost technology demonstration of the kinetic impactor technique to divert a hazardous asteroid. DART's primary objectives are to:

- Perform a full-scale demonstration of the spacecraft kinetic impact technique for deflection of an asteroid by targeting an object large enough to qualify as a potentially hazardous asteroid.
- Confirm and measure the resulting asteroid deflection by telescopic observations.
- Improve the understanding of high-speed collision effects on an asteroid and thereby improve the validation of performance models by constraining the momentum transfer enhancement due to ejecta through comparison to pre-impact predictions.

To achieve these objectives the DART spacecraft will intercept the secondary of the binary near-Earth asteroid 65803 Didymos. The primary member of the binary system will be referred to as Didymos and the secondary as Dimorphos. The system as a whole is also referred to as Didymos.

As part of the baseline level 1 Mission Investigation requirements the DART project shall obtain data, in collaboration with ground-based observations and data from another spacecraft to constrain the location and surface characteristics of the impact site and to allow the estimation of the dynamical changes in the Didymos system resulting from the DART impact and the coupling between the body rotation and the orbit.

1.2 Lowell Telescopic Observations

To interpret the deflection due to the DART impact, equally high-quality lightcurves of the Didymos system must be available from periods both prior to and following the DART impact. The Lowell Discovery Telescope (LDT) will be used with the Large Monolithic Imager (LMI, see Section 4.1) to obtain these data products. The data will include for each night of observation raw fits images, calibrated (flat field corrected, bias subtracted, trimmed) versions of these images with associated calibration frames, data tables of measured Didymos photometry, and PNG files identifying the calibration stars used for photometric processing.

The Lowell Observatory is contracted to acquire telescopic data in support of the DART mission. The telescopic data are archived by the DART project. Didymos and Dimorphos will be sufficiently far from the Earth and are sufficiently close together that they will not be resolved from one another, but instead will appear as a single point of light in these measurements. When Didymos is referred to below, it can be taken to be referring to the system as a whole rather than the primary body, unless otherwise specified.

The Lowell Discovery Telescope (LDT) is a Ritchey-Chrétien telescope with a 4.3-meter mirror located in the Coconino National Forest in Arizona, and owned and operated by Lowell Observatory. The DART observations are obtained with the Large Monolithic Imager (LMI, see Section 4.1). The data include for each night of observation raw fits images, calibrated (flat field corrected, bias subtracted, trimmed) versions of those images with associated calibration frames, data tables of measured Didymos photometry, and png files identifying the calibration stars used for photometric processing.

2 Applicable Documents and Constraints

This Data Product SIS is consistent with the following Planetary Data System documents:

1. Planetary Data System Standards Reference, Version 1.14.0.0, May 20, 2020
2. PDS4 Data Dictionary, Abridged, Version 1.14.0.0, Mar 23, 2020
3. PDS4 Information Model Specification, Version 1.14.0.0, Mar 23, 2020
4. Fits Standard document, version 4.0, July 22, 2016

This SIS is responsive to the following DART documents:

5. DART Data Management and Archive Plan (DMAP), Rev C, 24 May 2021

3 Relationships with Other Interfaces

Changes to the data products described in this SIS may affect the documents listed in 4.3.1. In the event of a conflict between this SIS and the DART DMAP, the DMAP takes precedence.

4 Data Product Characteristics and Environment

4.1 Instrument Overview

The visible-wavelength, direct-imaging CCD for the Lowell Discovery Telescope (LDT) is called the Large Monolithic Imager (LMI). LMI is a deep depletion, back illuminated monolithic CCD with 6144 x 6160 pixels. The instrument was funded by the National Science Foundation through AST-1005313. The camera is mounted in the direct through-put port on the LDT instrument cube.

LMI images a 12.3 arcminute square field of view with 15-micron pixels. The unbinned detector provides a pixel scale of 0.12 arcsec/pixel. The chip is commonly binned at 2x2 (0.24 arcsec/pixel) or 3x3 (0.36 arcsec/pixel). The chip is linear up to 65k ADU at the default gain of 2.89 e-/ADU. Read noise is 2.1 ADU per pixel and the readout time is 73 seconds for unbinned images, 24 seconds for 2x2 binning, and 10 sec for 3x3 binning. The CCD quantum efficiency is 80% from 400-700 nm, and dropping to ~50% at 350 and 900 nm.

Dual filter wheels in the LDT instrument cube provide 18 filter slots. A wide range of facility filters are available including Johnson-Cousins UBVRI, SDSS u'g'r'i'z', a variety of comet filters (OH, NH, CN, C3 CO+, C2, H2O), and a broad VR filter that provides >80% transmission from 500-700 nm. In addition there are continuum filters: UC (UV continuum), BC (blue continuum), GC (green continuum), RC (red continuum).

4.2 Data Product Overview

The specific data products described by this SIS are:

1. Raw Image Data
2. Calibrated Image Data
3. Master Bias Data
4. Flat Frame Data
5. Reference Star Data
6. Photometry Tables

4.3 Data Processing

All data processing is performed at Lowell Observatory. This section provides general information about data product content, format, and size.

4.3.1 Data Processing Level

The following table describes the products and their data processing levels.

Lowell Product	NASA Product Level	Description
Raw Image	Level-0	raw images
Calibrated Image	Level-2	calibrated image frame
Master Bias	Level-2	master bias frame
Master Flat Frame	Level-2	master flat frame
Reference Star	Level-2	PNGs of reference stars used for astrometric and photometric calibration.
Photometry Tables	Level-2	Photometry tables

4.3.2 Data Product Generation

All Lowell data products are generated by Lowell Observatory and transferred to the DART SOC. The DART SOC then generates PDS4 labels for each data product.

4.4 Data Products

This section gives a more detailed description of each data product, including the process by which the product is generated.

4.4.1 Raw Image Data

Fits images obtained with the Large Monolithic Imager (LMI) at the Lowell Discovery Telescope (LDT). Raw image data includes sky frames, bias frames, and flat fields. Dome flat fields are obtained by taking images of an illuminated white screen on the inside of the LDT dome. In some situations, additional observations of the twilight sky can be used as an alternate source for flat fields.

For all LDT observations, except those taken on the night of UT 2021-02-17, the telescope was tracked at sidereal rates so that the asteroid moved across a fixed set of field stars. On UT 2021-02-17, the telescope was tracked at one half the non-sidereal rates of the asteroid so that the field stars and asteroid trailed by equal amounts, roughly 1.3", which was comparable to the measured seeing on that night.

4.4.2 Calibrated Image Data

Calibrated sky frames that have been bias subtracted, flat field corrected, and trimmed. See section 4.4.6 for details of the Data Flow. Note that the pixels in the calibrated images are still in units of DN.

4.4.3 Master Bias and Flat Frame Data

Median combined stacks of bias and flat field images are used to create master calibration frames. The application of these master frames to the raw data, e.g. bias subtraction and division by the normalized flat field, result in the calibrated image data.

4.4.4 Reference Star PNG

PNG images for each sky frame where the photometric (PanSTARRS: Chambers et al. 2016) and astrometric (Gaia DR2: Brown et al. 2018) reference stars used in the photometric reductions are marked.

4.4.5 Photometry Table Data

ASCII summary table of the measured photometry of Didymos on each sky frame. The format of the table is specified in section 5.1.2

4.4.6 Data Flow

This section provides a high-level overview of how the calibrated image data are created from the Raw Image data, how master bias and flat frames are created, how the reference stars are used, and how the lightcurve tables are generated.

Raw image data are calibrated in three steps: (1) all images are trimmed down to just the useful part of the array as specified in the TRIMSEC header keyword, (2) a median combined master bias frame is subtracted from each flat field and sky image, and (3) a median combined, normalized flat field is divided into each sky frame. The master flat field is normalized by the median pixel value in the combined flat frame.

The photometry of Didymos is measured using the open source PHOTOMETRYPIPELINE package (Mommert, M., 2017. PHOTOMETRYPIPELINE: An automated pipeline for calibrated photometry. *Astronomy and Computing*, 18, pp.47–53). This pipeline astrometrically registers images based on the measured position of Gaia DR2 stars in the field, photometrically calibrates the zero point of the images based on the measured flux of field stars that have known catalog magnitudes (typically from the PanSTARRS catalog), and then using these astrometric and photometric solutions derives a calibrated magnitude for Didymos. The PNG files and photometry tables included in this dataset are outputs of this pipeline. The pipeline is built upon the tools SExtractor (E. Bertin and S. Arnouts. SExtractor: Software for source extraction. *A&AS*, 117:393–404, June 1996. doi:10.1051/aas:1996164) and SCAMP (Bertin 2006: Automatic Astrometric and Photometric Calibration with SCAMP, ASP Conference Series, Vol. 351, 2006, C. Gabriel, C. Arviset, D. Ponz, and E. Solano, eds., p. 112).

All observations of Didymos were obtained with a broad VR-band filter (>50% throughput from roughly 520-700 nm) and calibrated to r-band magnitudes in the PanSTARRS catalog. Solar type stars were always used for calibration. The pipeline defines solar-like colors as being within 0.2 magnitudes of the Sun's g-r (0.44) and r-i (0.11) colors.

A small subset of the raw fits images were not successfully registered with an astrometric solution by the Photometry Pipeline (Mommert 2017). In those cases, measuring the photometry of field stars (for calibration) and

of Didymos was not possible. Associated calibrated fits images are thus not included for raw images that failed this processing step, hence the discrepancy between the number of raw and calibrated images.

For a subset of the png files, the positions of stars in the reference catalog (indicated by red circles) do not match up with sources in the measured frames. When this happened, the entire set of catalog positions were generally offset from the actual sources by <10 arc seconds. The cause of this offset remains unclear, however the resulting photometry for these frames is valid and of comparable quality to surrounding frames that do not have this issue of offset positions in the png file.

4.4.7 Labeling and identification

Raw and Calibrated Images

Raw and calibrated images consist of a single fits file containing the raw image and an associated XML file. They are named according to the following convention.

lmi_<yyyymmdd>_<image counter>_<product type>_<version>.<ext>

where:

filename section	Description
lmi	Refers to the Large Monolithic Imager instrument
<yyyymmdd>	year, month, day of observing session in UT
<image counter>	four-digit image counter for observing session, reset for each night of observation. Counter starts at 0001
<product type>	defines product as one of the following types: <ul style="list-style-type: none"> • raw • cal – calibrated
<version>	the version of the data product. ex “v1” or “v2”.
<extension>	the file extension. “.fits” for fits file format, “.xml” for the PDS label.

Ex. lmi_20201217_0157_raw_v1.fits is a raw image product for a 2020-12-17 observing session.

Reference Star PNGs

For each calibrated image there are two associated PNGs of reference stars. One is the astrometry reference and the other is the photometry reference.

<cal fits filename>_<product_type>_<version>.png

where:

filename section	Description
<cal fits filename>	calibrated image fits filename as defined above. Ex. lmi_20201217_0062_cal_v1.fits
<product type>	defines product as one of the following types: <ul style="list-style-type: none"> • astro – astrometry reference • photo – photometry reference
<version>	the version of the data product. ex “v1” or “v2”

These PNGs are referenced in the calibrated image label via File_Area_Observational_Supplemental.

Master Bias and Flat Field Frames

For each observing session the calibrated images are generated from the raw images using master_bias.fits and master_flat_vr.fits calibration frames. The "vr" string in the master flat field name refers to the broadband filter in which the observations were obtained. The {ProductID} for these data products contains the observation date, allowing for a unique LID for each master file (see Section 5.1).

Photometry Table

The photometry summary table is named according to the following convention:

ldt_<YYYYMMDD>_didymos_photometry.dat

where:

ldt – refers to the Lowell Discovery Telescope

<YYYYMMDD> is the year, month, day of the observing session in UTC.

Ex. ldt_20201215_didymos_photometry.dat

4.5 Standards used in Generating Data Products

4.5.1 PDS Standards

All data products described in this SIS conform to PDS4 standards as described in the PDS Standards document noted in the Applicable Documents section of this SIS. Prior to public release, all data products will have passed a data product format PDS peer review to ensure compliance with applicable standards.

4.5.2 Time Standards

Time standards used by the DART mission conform to PDS time standards.

4.5.3 Coordinate Systems

All coordinate systems used by the DART mission conform to IAU standards.

4.5.4 Data Storage Conventions

All raw fits files store the image data as MSB 16-bit integers. All calibrated fits files and the master calibration files store the image data as 64-bit floats. The photometry table is stored as UTF-8 ASCII.

4.6 Data Validation

Data validation falls into two types, validation of the science data and validation of the compliance of the archive with PDS archiving and distribution requirements. The first type of validation will be carried out by the SOC and the Investigation Team, and the second will be overseen by the PDS, in coordination with the SOC.

The formal validation of data content, adequacy of documentation, and adherence to PDS archiving and distribution standards is subject to an external peer review. The peer review will be scheduled and coordinated by the PDS. The peer review process may result in "liens," actions recommended by the reviewers or by PDS personnel to correct the archive. All liens must be resolved by the SOC. Once the liens are cleared, PDS will do a final validation prior to packaging and delivery. When data are prepared for submission to PDS, the SOC will use PDS-provided validation tools to ensure conformance to PDS standards.

Continuous validation of the data products will be performed throughout the mission, as the Project will be utilizing the PDS4 data products as they are generated and the data do not exist in any form other than PDS4 data products.

5 Detailed Data Product Specifications

The following sections provide detailed data product specifications for the Lowell data products.

5.1 Data Product Structure and Organization

The highest level of organization for a PDS archive is the bundle. A bundle is a set of one or more related collections which may be of different types. A collection is a set of one or more related basic products which are all of the same type. Bundles and collections are logical structures, not necessarily tied to any physical directory structure or organization.

A unique identifier is assigned to each PDS4 product. This is known as the logical identifier, or LID. All LIDs consist of a series of colon-separated segments. The complete rules for formulating LIDs are in the PDS4 Standards Reference. An example of the LID structure is shown below:

```
urn:nasa:pds:{BundleID}:{CollectionID}:{ProductID}
```

The bundle XML label stops at the {BundleID}. Each collection label stops at {CollectionID}. Products within a collection contain all segments. The LID allows each data product to be uniquely identified, even if the filenames are the same, as in the case of the Master Bias and Master Flat Field products (see Section 4.4.7).

The Lowell PDS archive is part of the DART Telescopic Observation Bundle. The Lowell data collections are the "data_Idtraw", "data_Idtcal", and "data_Idtddp", where "Idt" refers to the Lowell Discovery Telescope. Documentation such as the SIS is organized in the "document_Idt" collection.

The Lowell data collections are stored in a directory tree organized by collection name then by date of observation. This structure allows a user to determine which collection is desired, then navigate to a specific observing date, and finally browse the data product files.

The directory structure for the Lowell collections is shown below. The "data_Idtraw" folder contains the raw fits files and their associated XML labels. The "data_Idtcal" folder contains the calibrated fits file, reference star PNGs, and master calibration fits files used to calibrate the data. Lowell light curve data associated with the observation is contained in the derived data product folder, "data_Idtddp".

Ex.

```
root/  
  document_Idt/  
  data_Idtraw/  
    Idt_YYYYMMDD  
  data_Idtcal/  
    Idt_YYYYMMDD  
  data_Idtddp/  
    Idt_YYYYMMDD
```

The subdirectories under each collection directory are organized by the date of the observation: "Idt" refers to the Lowell Discovery Telescope and "YYYYMMDD" is the UTC YearMonthDay of the observation.

5.1.1 Image Fits Files

Image data products are stored in the fits file format with a detached PDS label. The detached PDS labels are PDS4 compliant XML labels that describe the contents of the image file and record the significant portions of the fits header for data processing and interpretation. The following table describes the format and content of the fits header. The Class.Attribute Name column shows the mapping of the fits keyword to the class and attribute in the PDS4 XML label. Blank fields indicate where the metadata only exists in the fits keyword.

Class.Attribute Name	Keyword and example	Description
n/a	SIMPLE = T	required in fits standard.
element_array.data_type	BITPIX = 16	number of bits per data pixel
axes	NAXIS = 2	number of data axes
axis_array.sequence_number	NAXIS1 = 2096	length of data axis 1. Equivalent to PDS 'sample'
axis_array.sequence_number	NAXIS2 = 2054	length of data axis 2. Equivalent to PDS 'line'.
	BSCALE = 1	default scaling factor
element_array.value_offset	BZERO = 32768	offset data range to that of unsigned short. Does NOT exist in the calibrated or master fits files
	BUNIT = 'ADU'	pixel units (ADU, electrons)
	OBSERVER = 'Moskovitz'	name of observer
	OBSERVAT = 'Lowell Observatory'	observatory name
	ALTITUDE = 2361.	altitude of observatory in meters
	LATITUDE = 34.7443	latitude of observatory in degrees
	LONGITUD = -111.4223	longitude of observatory in degrees
	OBSREF = 'WGS84'	the coordinate system for LONGITUD and LATITUDE
Time_Coordinates.start_date_time	DATE = '2020-12-17T00:03:13.22'	UTC date (yyyy-mm-ddTHH:MM:SS.ss) of observation
Target_Identification.name	OBJNAME = 'Bias'	target object name
	OBJECT = 'Bias'	target object name. same as OBJECT. Kept to facilitate processing.
Target_Identification.type	OBSTYPE = 'BIAS'	target type (object, flat, bias)
	IMAGETYP = 'BIAS'	target type (object, flat, bias). same as OBSTYPE. Kept to facilitate processing
	DATE-OBS = '2020-12-17T00:03:13.22'	UTC date (yyyy-mm-ddTHH:MM:SS.ss) of observation
img:exposure_duration	EXPTIME = 0.	actual integration time, sec
	UTCSTART = '00:03:13.22'	start time of exposure in UTC HH:MM:SS.ss
	UT = '00:03:13.22'	start time of exposure in UTC. Same as UTCSTART. Kept to facilitate processing.
Time_Coordinates.stop_date_time	UTCEND = '00:03:15.46'	end of exposure in UTC HH:MM:SS.ss
	TRIMSEC = '[18:2063,3:2052]'	The x,y pixel ranges on the data array that contain useful data. The section is in binned pixels and is indexed starting at 1. [x1:x2, y1:y2]. The data array includes pixels from x1 to x2-1 and y1 to y2-1.
	BIASSEC = '[2067:2092,3:2052]'	The x,y pixel ranges on the data array that contain overscan data. The section is in binned pixels and is

Class.Attribute Name	Keyword and example	Description
		indexed starting at 1. [x1:x2, y1:y2]. The data array includes pixels from x1 to x2-1 and y1 to y2-1.
	CCDSUM = '3 3'	CCD on-chip bin factors applied during readout, given as the number of pixels summed in the x and y directions.
	GAIN = 2.89	CCD Gain in electrons per ADU
	RDNOISE = 2.1	CCD Read Noise in ADU
	DETECTOR = 'CCD231-C6-F08_SN-10382-14-01'	CCD detector name
	DETSIZE = '6144x6160'	Size of detector in unbinned pixels
	PIXISIZE = 15	Physical size of pixels in micrometers
	PIXSCAL = 0.12	Angular size of unbinned pixels on one side in arcseconds
	SCALE = 0.36	Angular size of pixels on one side in arcseconds after binning applied
	DETTEMP = -119.9074	Detector temperature in degC
	TEMPCCD = -119.9074	Detector temperature. in degC. Duplicate included for software compatibility.
	CCTEMP = 12.47616	cold tip temperature in degC.
Observing_System_Component	TELESCOP = 'DCT'	telescope name, Discovery Channel Telescope, old designation for Lowell Discovery Telescope.
	LST-OBS = '22:21:50.400'	local sidereal time of exposure start
geom:Reference_Frame_Identification	EQUINOX = 2000.	epoch of equinox for RA and DEC
	AIRMASS = 1.	Airmass of observation
	TELEFOCUS = 150.	telescope focus position in microns
	HA = '00:40:44'	hour angle [hh:mm:ss]
	ZA = 0.	zenith angle in deg
	ZD = 0.	zenith angle. same as ZA. kept to facilitate processing.
	PARANGLE = 3.23	The parallactic angle is the angle in deg formed at the on-sky location of a given object by the intersection of arcs drawn from the object to zenith and from the object to the celestial pole.
geom:right_ascension_angle	RA = '21:41:06.130'	right ascension [hh:mm:ss.sss]
geom:declination_angle	DEC = '+34:34:44.50'	declination [deg:mm:ss]
	ST = '22:21:50.400'	local sidereal time of exposure start
	TELALT = 90.	telescope altitude angle at start of exposure
	TELAZ = 180.	telescope azimuth angle at start of exposure
	OBSLAT = 34.7443	latitude of observatory in degrees. same as LATITUDE. Duplicate included for software compatibility.
	OBSLONG = -111.4223	longitude of observatory in degrees. same as LONGITUD. Duplicate included for software compatibility.
	OBSALT = 2361.	altitude of observatory in meters. same as ALTITUDE. Duplicate included for software compatibility.
	INSTRUME = 'LMI'	instrument

Class.Attribute Name	Keyword and example	Description
	FILTERS = 'DARK'	composite filter name
	PRESSURE = 1022.	air pressure, adjusted to sea level in mBars
	TEMPAMB = 2.5	mean ambient temperature in degC
	TEMPDEW = -11.	Dew point in degC
	HUMIDITY = 36.	relative humidity in percent
	WINDDIR = 113.	mean wind direction, N through E in deg
	WINDVEL = 2.3	mean wind speed in m/s
geom:celestial_north_clock_angle	SKYVPA = 0.	The orientation of the x-y axes of the CCD relative to celestial north measured in degrees east of north
	RADECSYS = 'FK5'	astronomical coordinate system

5.1.2 Photometry ASCII table files

Photometry data are stored as a PDS4 ASCII fixed-width table according to the following format. Note that Field Location uses the PDS4 definition, which is the location, in bytes, of the first character in the field and that location counting begins at one, not zero. Note that astronomical magnitudes are dimensionless. Thus, the 'mag', 'sig', 'ZP', 'ZP_sig', 'inst_mag', 'in_sig' values are all unitless values.

Field	Field Number	Description	Field Location (Bytes)	Length (Bytes)
file	1	file name of the calibrated image where data were measured	1	29
julian date	2	Julian date of the exposure midtime in units of julian days	31	15
mag	3	Calibrated PanSTARRS r-band apparent magnitude of Didymos	47	7
sig	4	1-sigma error on the apparent magnitude	55	6
ZP	5	Calibrated zero point magnitude in PanSTARRS r-band	62	7
ZP_sig	6	1-sigma error on the zero point magnitude	70	6
inst_mag	7	Instrumental magnitude of Didymos	77	8
in_sig	8	1-sigma error on the instrumental magnitude	86	6
SExtractor_flag	9	Flags associated with the Source Extractor photometry measurements, see source_extractor_flags.txt (urn:nasa:pds:dart_tele	93	15

		obs:document_idt_source_extractor_flags) in the documents collection for more detailed description.		
aprad	10	Radius in pixels of the aperture used for the photometry measurement (units of pixels). The binned image scale for Large Monolithic Imager is 0.36 arcs/pixel	109	5

5.2 Label and Header Descriptions

All Lowell data products contain time and date information that can be used to sort and correlate data products. The XML labels define the size and location of the header information in the data file and the byte offset at which the data starts.

6 Applicable Software

6.1 Utility Programs

At the current time the DART project has no plans to release any mission specific utility programs.

6.2 Applicable PDS Software Tools

Data products found in the DART Telescopic Observations Bundle can be viewed with any PDS4 compatible software utility. Image data are formatted as fits data files which can be read by any fits compatible software viewer or fits library.

6.3 Software Distribution and Update Procedures

As no DART specific software will be released to the public, this section is not applicable.