Las Campanas Observatory Software Interface Specification for Data Collected in Support of DART Mission

Version 1.0

Technical Content Approval

Prepared/Approved by:

David Osip
LCO Lead

Olivier Barnouin	Ray Espiritu

Approved by:

Ed Reynolds Project Manager	Elena Adams Mission Systems Engineer
Andy Cheng Investigation Team Lead	Nancy Chabot Coordination Lead

Revision Log

Rev	By	Description	Date
-	D. Osip	Initial Release	06/05/2022
	D. Osip	Revision	19/08/22
	D. Osip	Revision	01/12/22

1. Purpose and Scope

This Software Interface Specification (SIS) specifies the data products (uncalibrated and calibrated) from the Las Campanas Observatory DART support campaigns at the Magellan Baade 6.5m and Swope 1m telescopes. David Osip from Carnegie's Las Campanas Observatory (LCO) is responsible for producing these data products and distributing them to the DART SOC for redistribution to the DART Investigation Team and the Planetary Data System (PDS).

This document provides detailed descriptions of all data products including data sources and recipes for how they are generated. Intended users include investigators associated with the DART mission as well as others in the general planetary science community.

1.1. DART Mission Purpose and Goals

NASA's Double Asteroid Redirection Test (DART) will be the first space experiment to demonstrate asteroid impact hazard mitigation by using a kinetic impactor. The target is the near-Earth binary asteroid 65803 Didymos. The DART spacecraft is designed to impact the secondary in the (65803) Didymos system (Dimorphos), and to modify its trajectory through momentum transfer.

DART has four level 1 requirements to meet in order to declare mission success:

(1) impact Dimorphos between 2022 September 25 and October 2
(2) cause at least a 73 s change in its binary orbit period via the impact
(3) measure the change in binary period to an uncertainty of 7.3 s or less
(4) measure the momentum transfer efficiency (β) of the impact and characterize the resulting effects of the impact.

1.2. LCO DART Support Observations

The realization of requirements 3 and 4 can be achieved via one task: precision photometric light curve measurements of the Didymos system. To interpret the deflection due to the DART impact, high precision photometric lightcurves of the Didymos system must be available from periods both prior to and following the DART impact.

Carnegie's Las Campanas Observatory (LCO) is contracted to acquire telescopic observations in support of the DART mission. The Magellan Baade 6.5m telescope using the Inamori-Magellan Areal Camera & Spectrograph (IMACS) and from the Swope 1m telescope using the facility 4K CCD camera will obtain time series wide field CCD images. The 6.5-meter Baade and Clay telescopes were built by the Carnegie Institution of Washington at Las Campanas Observatory in Chile on behalf of the Magellan Project, a collaborative effort by the Carnegie Institution, University of Arizona, Harvard University, University of Michigan, and Massachusetts Institute of Technology. The principal foci are f/11 at the two Nasmyth locations and a wide field of view is provided by the Gregorian secondary design. The Swope 1m telescope is an f/7 Ritchey-Chrétien with a Gascoigne corrector providing a well-corrected field about 3 degrees in diameter. From both facilities, for each night of observation, data will include both raw and calibrated FITS images along with calibration recipes and data tables providing time series photometry of Didymos. All obtained data are archived by the DART project.

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:

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

This SIS is consistent with the following documents:

1. Greisen, E. W., and Calabretta, M. R., 2002, Representations of World Coordinates in FITS, Astronomy and Astrophysics, 395, 1061-1075.
2. Ginsburg, Adam, et al. "Astroquery: an astronomical web-querying package in Python." *The Astronomical Journal* 157.3 (2019): 98
3. De Angeli, F., et al. "Gaia Data Release 3: Processing and validation of BP/RP low-resolution spectral data." *arXiv preprint arXiv:2206.06143* (2022).
4. Becker, Andrew. "HOTPANTS: High Order Transform of PSF ANd Template Subtraction." *Astrophysics Source Code Library* (2015): ascl-1504.

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

Swope 4K CCD is the visible-wavelength, direct-imaging CCD for the Swope 1m Telescope at LCO. The camera images a 29.7 x 29.8 arc minute field of view at 0.435"/pixel spatial resolution for unbinned 15 micron pixels. The detector is normally read out in a quad amplifier mode writing to four separate FITS files. Readout time is 37s for the unbinned 4 amplifier mode. Facility filters include Harris BVRI and Sloan griz, with the Sloan r' adopted for this observing campaign.

IMACS is a reimaging spectrograph mounted permanently on the Magellan Baade Telescope. The f/2 camera provides a 27.4 arcmin diameter field at a scale of 0.200 arcsec per pixel across the CCD mosaic array employing eight thinned CCDs manufactured by E2V to produce a 8192 x 8192 pixel mosaic. These CCDs are all 2K x 4K x 15-micron devices. Each detector thus provides a ~6.8' x 13.6' FOV. This campaign has opted to use a single CCD (CCD02) out of the eight in the mosaic array for all Didymos observations. Unbinned full frame readout for the arrays is ~82 seconds, while 2x2 binning can reduce the readout to 29 seconds. A wide range of facility filters are available including the SDSS r' (also referred to as the "Sloan_r" filter) being deployed for this campaign.

4.2. Data Product Overview

The specific data products described by this SIS are:

1. Raw Image Data
2. Reduced and Calibrated Image Data
3. Photometry Tables

4.3. Data Processing

All data reduction and analysis is carried out at Las Campanas 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.

LCO Data Product	NASA Product Level	Description
Raw Image	Level-0	Raw images (FITS)
Calibrated Image	Level-2	Calibrated image frame (FITS)
Photometry Tables	Level-2	Photometry tables (ASCII)

4.3.2. Data Product Generation

All LCO data products are generated by Las Campanas 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 (IMACS and Swope)

FITS images obtained with the Inamori-Magellan Areal Camera and Spectrograph (IMACS) instrument on the Magellan-Baade telescope at Las Campanas Observatory (Dressler et al. 2011) are written as individual frames for each of the 8 IMACS detectors in the f/2 CCD array. FITS images produced for this archive only utilize one of the detectors: CCD02. Raw image data include bias frames, sky frames and flat fields, with an overscan region on images used for bias-level subtraction. Dark current is typically very low when imaging with IMACS, and dark frames are typically not used. Dome flat fields may be obtained by taking images of a pupil-mask screen illuminated by telescope-mounted lamps. Additional observations of the twilight sky can be used as an alternate source for flat fields. For the IMACS images, sidereal tracking was used, and Didymos was allowed to move across the field.

FITS images obtained with the 4K CCD camera on the Swope 1m telescope at Las Campanas Observatory are written as individual frames for each of the 4 detector amplifiers that are read out. Raw image data include bias frames, sky frames and flat fields, with an overscan region on images used for bias-level subtraction. Dark current is typically very low when imaging with the 4K CCD (especially considering the short exposures adopted for this campaign), and dark frames are typically not used. Dome flat fields may be obtained by taking images of a dome-mounted screen illuminated by telescope-mounted lamps. Additional observations of the twilight sky are more typically used for accurate flat fields. For the Swope 4K CCD images, sidereal tracking was used, and Didymos was allowed to move across the field.

See 4.4.3 Fits Image Targets for a description of the target values in the fits header and PDS4 label.

4.4.2. Reduced & Calibrated Image Data

FITS images on sky for the target Didymos are identified by the associated PDS4 label with Target_Identification name set to "(65803) Didymos" (see section 4.4.3). Calibrated sky frames have been bias subtracted, flat field corrected, and trimmed. See section 4.4.4 for details of the Data Flow. Note that the pixels in the calibrated images are still in units of DN. These images are also astrometrically registered and include a verified World Coordinate System (WCS). Note that the only images with the Didymos asteroid as the target are reduced and calibrated and included in the IMACS and Swope calibrated data collections.

4.4.3. Fits Image Targets

The following table shows the values for the OBJECT keyword in the Fits Header and the corresponding value of the Target_Identification.Name in the PDS4 label.

PDS4 Target_Identification.Name	**OBJECT keyword in fits header**	**Description**
(65803) Didymos	Didymos	Target is Didymos asteroid
Bias	Bias	Image used for Bias subtraction
Dome Flat	DomeFlat	Dome mounted screen, used for Flat Field
Sky	TwiFlat	Twilight sky observation, used for flat field
Dark	Dark	Image used for dark current subtraction

4.4.4. Photometry Table Data

This data product is an ASCII table of the measured photometry of Didymos on each object frame. The format of the table is specified in section 5.1.2.

4.4.5. Data Flow

This section provides a high-level overview of how the Calibrated Image data are created from the Raw Image data.

Flat field images were obtained by either imaging the sky during twilight or taking images of a pupil-mask screen illuminated by telescope-mounted lamps (in the case of IMACS) or images of the dome-mounted screen (in the case of Swope 4K CCD). The overscan region in these flat field images was subtracted to remove the bias level, and these bias-subtracted images were normalized and median combined to create a flat field for the night. Target images were also bias-subtracted using their overscan regions, and then divided by the nightly flat field. Swope 4K CCD images were reconstructed as single full frame images from the reduced flat fielded frames for each for the detector quadrants. At this point, the files are also attached to a World Coordinate System (WCS), and appropriate keywords attached as per the WCS standard for FITS files (Greisen et al. 2002a, 2002b, 2006). A precise astrometric solution is achieved with an iterative process, starting with a preliminary solution created using the WCS package of astropy library using the known parameters of the images (coordinates, rotation of the field, pixel scale), and improved with successive matching between the real stars x-y coordinates in the images and the x-y coordinates of a catalog of GAIA stars in the field resulting from the astrometric solution.

Instrumental aperture photometry is measured in every image on the asteroid's and on the selected stars' positions, for a set of apertures from 3 to 20 pixels radius, using the python package SEP (Barbary, K. 2016) for the initial detection of the brightest non-saturated stars and the subsequent background subtraction across the entire image, in order to measure the flux in the different apertures and transform directly into instrumental magnitudes.

In order to estimate the photometry zero points of the individual images, we use different python packages: astroquery (Ginsburg et al. 2019) to query Vizier and Horizon databases, in order to identify GAIA stars in our set of selected stars inside a 2 arcsecs tolerance radius,and to obtain the coordinates of the asteroid for the given date of the images; and gaiaxpy python package (De Angeli et al. 2022), to request and download synthetic photometry of GAIA stars (Gaia Collaboration, Montegriffo et al. 2022) in Sloan-r band when available. Final photometry of the Didymos-Dimorphos system is estimated adding the zero points to measured instrumental magnitude in the corresponding images.

For some of the IMACS observations an additional step was carried out as follows. Within each pointing, a sequence of the early flat-fielded images of Didymos and its surrounding star field were then combined to make a subtraction template for the later observations at the same pointing, while another sequence of flat-fielded images taken later in the sequence are used to create a second subtraction template for the earlier observations. The "**High Order Transform of PSF And Template Subtraction"** (Hotpants) image subtraction software (Becker 2015) was used to identify all of the sources on a frame and to remove sources from the region around Didymos, minimizing contamination from nearby stars, galaxies, etc. Aperture photometry was performed on Didymos and reference stars on each frame, using a variety of aperture sizes that were then selected based on image quality conditions for the night along with minimized photometric uncertainties. While the background sources were removed as just described when doing the photometry for Didymos on each frame, reference stars photometry was done on flat-field corrected but not background-subtracted frames. Reference stars tied to photometric catalogs (GAIA when available and PanSTARRS if not) were used to calculate a zero point for each frame.

4.4.6. Labeling and identification

Raw and Calibrated Images, IMACS

IMACS raw images were taken from a single CCD (CCD02) out of the eight CCDs in the IMACS imaging array. The raw IMACS images are stored in the data_lcoimacsraw collection and organized by observation night.

The raw product naming convention is as follows:
<camera reference><counter><CCD#>_<yymmdd>.<extension>

where:

filename section	Description
<camera reference>	'ift' refers to the IMACS f/2 camera
<counter>	four-digit image counter for observing session, reset for each night of observation. Counter starts at 0001
<CCD#>	CCD number 1-8 within the mosaic array for the IMACS focal plane. For this archive it is always 2
<yymmdd>	UTC year, month, day of observation
<extension>	the file extension. ".fits" for FITS file format, ".xml" for the PDS4 XML label

Ex. ift1001c2_220702.fits is a raw IMACS f/2 camera image corresponding to CCD02 in the array from the night of 2022-07-01/02.

Calibrated IMACS files follow the same naming convention but prepend 'r' to the camera reference (i.e. ift1001c2_220702.fits is processed to become rift1001c2_220702.fits). Note that only raw files targeting the Didymos asteroid are processed into calibrated files.

Raw and Calibrated Images, Swope

Swope 4K CCD raw images consist of 4 FITS files each corresponding to one of 4 readout amplifiers for the CCD. They are named according to the following convention.

<camera reference>c<counter><amp#>_<yymmdd>.<extension>

where:

filename section	Description
<camera reference>	'ccd' refers to Swope 4K CCD
<counter>	four-digit image counter for observing session, reset for each night of observation.
<amp#>	Readout amplifier 1-4
<yymmdd>	UTC year, month, day of observation
<extension>	the file extension. ".fits" for FITS file format, ".xml" for PDS4 XML label

Ex. ccd1001c1_220822.fits is a raw Swope 4k CCD image corresponding to readout amplifier 1 from the night of 2022-08-21/22.

Calibrated Swope 4K CCD files combine the 4 separate amplifier readout files such that the naming convention drops the <amp#> from the file name and prepends 'r' to the camera reference. The calibrated fits file stores the data from each of the four separate amplifier readout fits files into a single fits data cube.

Ex. ccd1001c1_220822,fits, ccd1001c2_220822.fits, ccd1001c3_220822.fits, ccd1001c4_220822.fits are processed to become rccd1001_220822.fits

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

photometry_<instrument>_<yymmdd>.tab

where <instrument> is either IMACS or Swope
<yymmdd> is the UTC year, month, day of observation

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 store the image data as 64-bit floats. The photometry table is stored as UTF-8 ASCII files.

Commented [RE1]:

4.6. Data Validation

Validation of the science data will be carried out by the DART SOC and the DART Investigation Team. Compliance of the provided data products with PDS archiving requirements will be overseen by the PDS in coordination with the DART 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.

5. Detailed Data Product Specifications

The following sections provide detailed data product specifications for the Las Campanas Observatory 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, which is not the case for this archive.

The Las Campanas Observatory PDS archive is part of the DART Telescopic Observation Bundle. The LCO data collections are listed by instrument and data processing level, e.g. “data_lcoimacsraw” (IMACS f/2 camera raw data), or “data_lcoswoperaw” (Swope CCD camera raw data). Documentation such as this SIS is organized in the "document_lco" collection.

The LCO 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 LCO collections is outlined below. For the IMACS f/2 camera observations, the “data_lcoimacsraw” folder contains the raw fits files, the “data_lcoimacscal” folder contains the calibrated fits, and derived data products including photometric light curve data derived from IMACS images are in the folder “data_lcoimacsddp”. Similarly for the LCO Swope 4k CCD camera, "data_lcoswoperaw" contains the raw Swope fits files, "data_lcoswopecal" contains the Swope calibrated fits files, and "data_lcoswopeddp" contains the photometric light curve data derived from Swope images.

```
Ex.
root/
 document_lco/
 data_lcoimacsraw/
    utYYMMDD
 data_lcoimacscal/
   utYYMMDD
 data_lcoimacsddp/
   utYYMMDD
data_lcoswoperaw/
    utYYMMDD
 data_lcoswopecal/
   utYYMMDD
```

data_lcoswopeddp/
utYYMMDD

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 PDS4 Class.Attribute Name column shows the PDS4 class and attribute in the PDS4 corresponding to the FITS Header keyword. Blank PDS4 Class.Attribute Name fields indicate where the metadata only exists in the fits keyword.

Raw IMACS FITS

Raw IMACS frames have the following keywords: [keywords marked with * are legacy items inherent to the LCO instrument software or are duplicate keywords added by the processing software]

PDS4 Class.Attribute Name	**FITS 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 = 1088	length of data axis 1. Equivalent to PDS ‘sample’
axis_array.sequence_number	NAXIS2 = 2112	length of data axis 2. Equivalent to PDS ‘line’.
	BSCALE = 1.0000	default scaling factor
element_array.value_offset	BZERO = 32768	offset data range to that of unsigned short. Does NOT exist in the calibrated fits files
	BUNIT = ‘DU/PIXEL’	pixel units (ADU, electrons)
	OBSERVER = ‘Osip’	name of observer
	TELESCOP = ‘Baade_Mag_1’	Telescope name
	SITENAME = LCO	Name of observatory
	SITEALT = 2405	altitude of observatory in meters
	SITELAT = -29.01423	latitude of observatory in degrees
	SITELONG = -70.69242	longitude of observatory in degrees
	TIMEZONE= 4	Hardcoded value identifying the local timezone associated with the local times reported in the fits header

PDS4 Class.Attribute Name	FITS Keyword and example	Description
	DATE-OBS= '2022-07-02T04:14:12'	UTC date-time (start)
	TIME-OBS= '04:14:12.3'	UTC time (start)
	UT-DATE = '2022-07-02	UTC date (start)
	UT-TIME = '04:14:12'	UTC time (start)*
	UT-END = '04:15:42'	UTC time (end)
	LC-TIME = '00:14:12'	local time (start)
	NIGHT = '01Jul2022'	local night in DDmmmYYYY
	INSTRUME= 'IMACS Short-Camera'	instrument name
	CCD-TYPE= 'E2V'	CCD type
	DEWAR = 'Mosaic3'	Dewar setting
	SCALE = 0.400	scale in units of arcsec/pixel
	EGAIN = 1.49	electrons/DU (nominal)
	ENOISE = 5.56	electrons/read (nominal)
	CDSTIME = 120	CDS time *
	CCDGAIN = 'High'	CCD gain *
	NCHIPS = 8	Number of chips (CCDs) in full IMACS configuration. Hardcoded. *
	CHIP = 2	Identifies CCD used to generate this fits file. Hardcoded to 2.
	CHOFFX = 213.893	x-offset [arcsec]
	CHOFFY = -416.809	y-offset [arcsec]
	RA = ' 22:05:27.4'	right ascension in hours:minutes:seconds format
	RA-D = 331.3642083	right ascension in degrees
	DEC = '-18:17:47.0'	declination in hours:minutes:seconds format
	DEC-D = -18.2963889	declination in degrees
	EQUINOX = 2000.00000	epoch of equinox of RA and DEC
	ASECS = 0.0	arcseconds *
	DSECS = 0.0	arcseconds *

PDS4 Class.Attribute Name	**FITS Keyword and example**	**Description**
	EPOCH = 2022.49911	epoch at start of exposure
	AIRMASS = 1.697	airmass at start of exposure
	TEL-ELEV= 36.07	telescope elevation in degrees above horizon
	ST = 65531.8	sidereal time: 18:12:11 (start of exposure)
	HA = -3.88766	hour angle in decimal hours (at start of exposure)
	HA-STR = 'E03:53:15'	hour angle in hour:minute:second format at start of exposure. E means east of meridian, W means west.
	GRAV-A1 = 12.53	IMACS/4 gravity angle (start) *
	GRAV-A2 = 12.88	IMACS/4 gravity angle (end) *
	GRAV-MIN= 12.53	IMACS/4 gravity angle (min) *
	GRAV-MAX= 12.88	IMACS/4 gravity angle (max) *
	ROTANGLE= 133.85	rotator offset angle Used to define direction to North as ROTANGLE+136.15
	ROTATORE= -113.06	rotator encoder angle
	G-SEEING= 0.00	guider seeing *
	CAL-LAMP= 'none'	calibration lamp(s) *
	FILENAME= 'ift1041c2'	original fits filename
	OBJECT = 'Didymos'	target object name
	COMMENT	Unused comment keyword. This is also added multiple times at the end of the fits header by the legacy software. *
	EXPTYPE = 'Object'	software enum of exposure type used (<object name>, "FLAT", "BIAS", or "DARK")
	EXPTIME = 90.000	exposure time [seconds]
	BINNING = '2x2'	type of binning used
	FILTER = 'Sloan_r'	filter name. All fits files were created with this filter.
	DISPERSR= 'f/2-Imaging'	disperser *
	G-ANGLE = 0.000	grating angle *
	SLITMASK= 'f/2-Imaging'	slit-mask *
	GISMO = 'none'	GISMO mask *
	DETFOCUS= 7375.7	detector-focus *

PDS4 Class.Attribute Name	FITS Keyword and example	Description
	L05FOCUS= 0.0	L05-focus *
	NSHUFFLE= 0	physical pixels *
	NOD-RA	N/A, added by legacy software *
	NOD-DEC	N/A, added by legacy software *
	STRDL-01	N/A, added by legacy software *
	STRDL-0N	N/A, added by legacy software *
	STRDL-02	N/A, added by legacy software *
	DWELTIME= 0.0	dwell time *
	NCYCLES = 0	shuffle cycles *
	SHUFNPOS= 0	shuffle positions *
	MMTF-X = 0	Etalon-X (parallelism) *
	MMTF-Y = 0	Etalon-Y (parallelism) *
	MMTF-Z = 0	Etalon-Z (spacing) *
	MMTF-CX = -1	Etalon-X (coarse) *
	MMTF-CY = 0	Etalon-Y (coarse) *
	MMTF-CZ = -1	Etalon-Z (coarse) *
	MMTF-FX = 5.83	Etalon-X (fine) *
	MMTF-FY = 5.66	Etalon-Y (fine) *
	MMTF-FZ = 7.63	Etalon-Z (fine) *
	MMTF-QX = 4.33	Etalon-X (quad-balance) *
	MMTF-QY = 4.02	Etalon-Y (quad-balance) *
	MMTF-QZ = 4.25	Etalon-Z (quad-balance) *
	SCRIPT = 'none'	script file *
	NLOOPS = 100	# of loops per sequence *
	LOOP = 5	# within this sequence *
	SPEED = 'Fast'	readout speed *
	NOVERSCN= 64	overscan pixels
	NBIASLNS= 64	bias lines

PDS4 Class.Attribute Name	FITS Keyword and example	Description
	BIASSEC = '[1025:1088,1:2048]'	The x,y pixel ranges on the data array that contain overscan data. The section is in binned pixels and is indexed starting at 1. [x1:x2, y1:y2]
	DATASEC = '[1:1024,1:2048]'	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]
	DEWARORI= 'Normal'	dewar orientation *
	SUBRASTR= 'none'	Hardcoded to none. All images are full frame
	TEMPCCD1= -166.0	CryoT temperature [degC]
	TEMPCCD2= -116.1	Platen temperature [degC]
	TEMPCCD3= -98.7	Chip-3 temperature [degC]
	TEMPCCD4= -111.2	Platen temperature [degC]
	TEMPCCD5= -116.1	Platen temperature [degC]
	TEMPCCD6= -159.5	CryoT temperature [degC]
	TEMPCCD7= -108.8	Platen temperature [degC]
	TEMPCCD8= -98.0	Chip-8 temperature [degC]
	TEMPSTR = 6.9	structure temperature [degC]
	VGAUGE = 0.00E+00	vacuum gauge [mbar]
	IONPUMP = 4.22E-07	ion-pump gauge [mbar]
	SOFTWARE=	software version ID
	FITSVERS= '3.13'	FITS header version *

Raw Swope Fits

Raw Swope 4K CCD frames have the following keywords:

PDS4 Class.Attribute Name	FITS 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 = 2176	length of data axis 1. Equivalent to PDS ‘sample’
axis_array.sequence_number	NAXIS2 = 2184	length of data axis 2. Equivalent to PDS ‘line’.

PDS4 Class.Attribute Name	FITS Keyword and example	Description
	BSCALE = 1.0000	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 = 'DU/PIXEL'	pixel units (ADU, electrons)
	ORIGIN = 'LCO/OCIW'	Name of site
	OBSERVER = 'Osip'	name of observer
	TELESCOP = 'Swope'	Telescope name
	SITENAME = LCO	Name of observatory
	SITEALT = 2280	altitude of observatory in meters
	SITELAT = -29.08300	latitude of observatory in degrees
	SITELONG = -70.69800	longitude of observatory in degrees
	TIMEZONE= 4	Hardcoded value identifying the local timezone associated with the local times reported in the fits header
	DATE-OBS= '2022-07-02'	UTC date (start)
	UT-DATE = '2022-07-02	UTC date (start) *
	UT-TIME = '04:14:12'	UTC time (start)
	UT-END = '04:15:42'	UTC time (end)
	LC-TIME = '00:14:12'	local time (start)
	NIGHT = '01Jul2022'	local night in DDmmmYYYY
	INSTRUME= 'Direct/4Kx4K-4'	instrument name *
	SCALE = 0.435	arcsec/pixel
	EGAIN = 1.040	electrons/DU (nominal)
	ENOISE = 3.40	electrons/read (nominal)
	NOPAMPS = 4	# of op-amps.Nominal is 4.
	OPAMP=3	op-amp ID used to generate this fits file.
	CHOFFX = 445.440	x-offset [arcsec]
	CHOFFY = -447.180	y-offset [arcsec]
	DISPAAXIS=0	disperser axis (for spectroscopic instruments)*
	RA = ' 22:05:27.4'	right ascension in hours:minutes:seconds format

PDS4 Class.Attribute Name	FITS Keyword and example	Description
	RA-D = 331.3642083	Right Ascension in degrees
	DEC = '-18:17:47.0'	declination in hours:minutes:seconds format
	DEC-D = -18.2963889	declination in degrees
	EQUINOX = 2000.00000	epoch of equinox of RA, DEC
	ASECS = 0.0	arcseconds *
	DSECS = 0.0	arcseconds *
	EPOCH = 2022.49911	epoch at start of exposure
	AIRMASS = 1.697	airmass at start of exposure
	ST = 65531.8	sidereal time in seconds: 18:12:11 (start of exposure)
	TELFOCUS=24011	telescope focus value
	CASSPOS=0.0	fixed position N-up and E-left
	FILENAME= ‘ccd0001c3'	original fits filename
	OBJECT = 'Didymos'	target object name
	COMMENT	unused comment keyword. Also added near end of fits header by legacy software. *
	EXPTYPE = 'Object'	software enum of exposure type used (<object name>, "FLAT", "BIAS", or "DARK")
	EXPTIME = 90.000	exposure time [seconds]
	NLOOPS=20	# of loops per sequence of exposures
	LOOP=1	Loop # within this sequence
	BINNING = ‘1x1'	binning used
	SPEED=‘Turbo’	enum of readout speed *
	NOVERSCN= 6128	overscan pixels in serial direction
	NBIASLNS= 128	bias lines (overscan in parallel direction)
	BIASSEC = '[2049:2176,2057:2184]'	The x,y pixel ranges on the data array that contain overscan data. The section is in binned pixels and is indexed starting at 1. [x1:x2, y1:y2]
	DATASEC = ‘[1:2048,1:2056]'	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]

PDS4 Class.Attribute Name	FITS Keyword and example	Description
	TRIMSEC = '[1:2048,1:2056]'	added by legacy software. Duplicate of DATASEC.
	FILTER = 'Sloan r'	Filter used. I found a case where there is an "r" filter used. Need to explicitly list ALL filters used by Swope for this dataset.
	WHEEL1 = 'Open'	filter in wheel 1
	WHEEL2 = 'Sloan r'	filter in wheel 2
	SUBRASTR = 'none'	Hardcoded to "none". All fits files are full frame
	TEMPCCD = -110.5	CCD temperature [degC]
	VGAUGE = 3.16E-05	vacuum gauge [mbar]
	IGAUGE = 3.26E-07	ion-pump gauge [mbar]
	SOFTWARE= Version 1.7.4 (1.0460) (May 7 2019, 11:20:24)	software version of CCD readout *
	FITSVERS= '1.2'	FITS header version *
	CHECKSUM= 'eEGIeEEIeEEIeEEI'	checksum of HDU generated by legacy software *
	DATASUM = '2209663690'	data unit checksum generated by legacy software *

Calibrated fits files have the following additional WCS keywords in addition to including most of those found in the raw frames:

PDS4 Class.Attribute Name	FITS Keyword and Example	
	WCSAXES = 2	
	CRPIX1 = 558.9662099735481	
	CRPIX2 = 1002.170041179001	
	PC1_1 = 0.0014340711385205	
	PC1_2 = -0.99999897171946	
	PC2_1 = 0.99999897171946	
	PC2_2 = 0.0014340711385205	
	CDELT1 = -0.00011	

	CDELT2 = -0.00011	
	CUNIT1 = ‘deg’	
	CUNIT2 = ‘deg’	
	CTYPE1 = ‘RA--TAN’	
	CTYPE2 = ‘DEC--TAN’	
	CRVAL1 = 331.2429940642	
	CRVAL2 = -18.244551416778	
	LONPOLE = 180.0	
	LATPOLE = -18.244551416778	
	RADESYS = ‘ICRS’	

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 is using the PDS4 starting index of 1.

Field	Field number	Description	Field Location (byte)	Length (bytes)
Julian date	1	Julian date at middle of exposure	1	14
Magnitude	2	Calibrated magnitude estimate	16	6
Uncertainty	3	Instrumental magnitude uncertainty associated with field 42	23	5
Flag	4	Binary flag to mark discrepant data. 0 = discrepant. 1=non-discrepant.	29	1
Filename	5	File name of the calibrated image where data were measured	31	20

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.