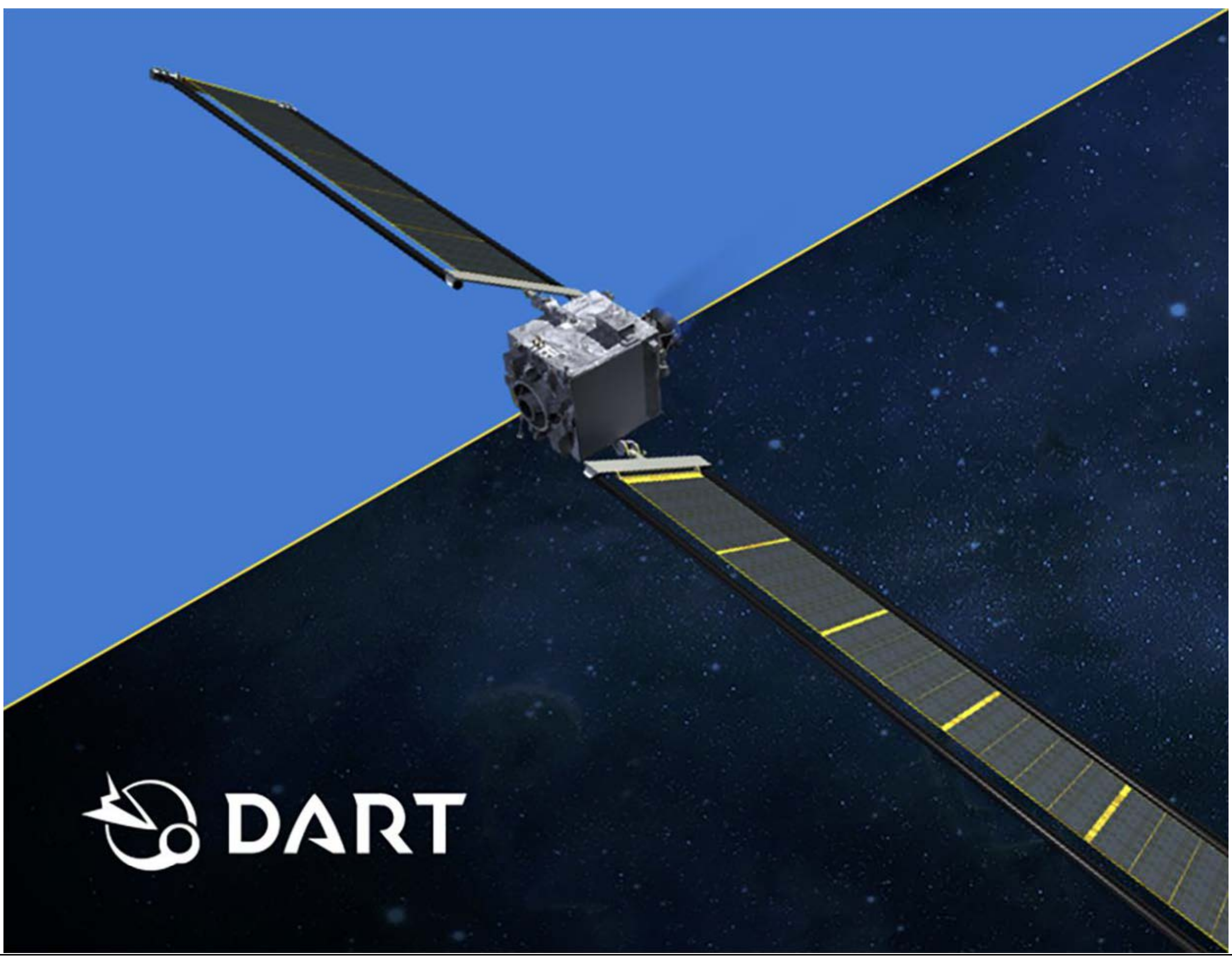
Shape Model Bundle Software Interface Specification

Double Asteroid Redirection Test (DART)



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Revision Log

Rev	By	Description	Date
0	O. Barnouin	Initial Release	28 Oct. 2021
0.1	O. Barnouin and R. Espiritu	Address comments from Terik Daly and R. Espiritu	29 Oct. 2021
0.2	R. Espiritu	Remove reference to example labels. No need to have them per feedback from DRACO PDS Peer Review.	01 Nov 2021
0.4	O. Barnouin and R. Espiritu	Changed SIS from collection to bundle	10 Aug 2023
0.5	O. Barnouin	Addressed reviewer liens from PDS review	24 Sept 2023
0.6	O. Barnouin	A few more liens to address	27 Oct 2023

CONTENTS

1. Purpose and Scope

This Software Interface Specification (SIS) describes the Double Asteroid Redirection Test (DART) asteroid shape (digital terrain) model products. The DART Science Operations Center (SOC) located at Johns Hopkins University Applied Physics Laboratory (APL) produces these data products and distributes them to the DART Investigation Team (IT) and the Planetary Data System (PDS).

This document provides users with a detailed description of the data products, how they were generated, and how they are organized in the archive. The document is intended to provide sufficient information to enable users to read and understand the data products. The intended audience is the scientists who will analyze the data, including those associated with the DART mission and those in the general planetary science community.

2. Applicable Documents and Constraints

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

1. Planetary Data System Standards Reference, Version 1.20.0, March 10, 2023
2. PDS4 Data Dictionary, Abridged, Version 1.20.0.0, March 10, 2023
3. PDS4 Information Model Specification, Version 1.20.0.0, March 10, 2023

This shape model SIS is responsive to the following DART documents:

1. DART Data Management and Archive Plan (DMAP), Rev C, 09 03, 2020
2. DRACO Uncalibrated/Calibrated Data Product Software Interface Specification, Version 0, December 15 2020
3. LICIACube Uncalibrated/Calibrated Data Product Software Interface Specification, Version 0, Oct 20 2021
4. Dimorphos Coordinate System Description, Oct 23, 2023 urn:nasa:pds:dart:document_draco:didymos_coordinate_system_description::1.0 - https://doi.org/10.26007/30x0-fv64
5. Didymos Coordinate System Description, Sept 21, 2023 urn:nasa:pds:dart:document_draco:dimorphos_coordinate_system_description::2.0 - https://doi.org/10.26007/7312-sc96

This shape model SIS is consistent with the following documents:

6. Rivkin, A.S., et al., 2021. The Double Asteroid Redirection Test (DART): Planetary Defense Investigations and Requirements. Planet. Sci. J. 2, 173. https://doi.org/10.3847/PSJ/ac063e
7. Daly, R.T., et al., 2022. Shape Modeling of Dimorphos for the Double Asteroid Redirection Test (DART). Planet. Sci. J. 3, 207. https://doi.org/10.3847/PSJ/ac7523
8. Daly, R.T., Ernst, C.M., Barnouin, O.S., et al., 2023. Successful Kinetic Impact into an Asteroid for Planetary Defense. Nature 1–3. https://doi.org/10.1038/s41586-023-05810-5

3. Relationships with Other Interfaces

Changes to the data products described in this SIS may affect the documents listed in Table 1. In the event of a conflict between the Shape (digital terrain) Model SIS and the DART DMAP, the DMAP takes precedence.

Table 1. Interface Relationships

Name	Type	Owner
DART Data Management and Archive Plan	Document	DART SOC

4. Data Product Characteristics and Environment

4.1. Calibrated Input Data Overview – Inputs to Shape Model Collection

This SIS describes the shape model data products produced by the DART Proximity Working Group. The primary inputs to each shape model in each collection are the calibrated Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO) images from the DART spacecraft and the LICIACube Unit Key Explorer (LUKE) images from LICIAcube spacecraft, as well as SPICE ancillary information. These data are processed through a variety of algorithms resulting in shape, topographic, and geometric information.

4.2. Data Product Overview

This SIS describes the derived stereophotoclinometry (SPC) data products produced by the DART project. These data products are PDS4 compliant ASCII or binary FITS files and ASCII text (OBJ) files with associated header information. They are generated at several stages of processing following DART's impact into Dimorphos, with a first quick release at a lower fidelity within a month of impact, and a more complete release at the best possible spatial resolution a few months later. Note that only some portions of the models have useful high spatial resolution information and are fairly obvious once a user looks at a given model. Regions that look smooth, or have sigma values of zero (see ancillary products) possess no image coverage. Specific details for each product can be found in Section 5. The suite of data products described in this SIS include:

1. **Surface Terrain and Tilt Maps** – A gridded terrain map of the surfaces of Dimorphos and Didymos, which provides the position of each pixel center in the body-fixed reference frame, a surface's tilt, and includes geopotential topography and slope. The geopotential topography provides the equivalent to topography defined on Earth, meaning topography relative to a geoid that is divided by the local acceleration due to gravity. In the case of Dimorphos, this topography includes the gravity effects of Didymos, but a single ref-potential value is used to compute this effective topography and so the result is difficult to interpret. The effects of Dimorphos pull on Didymos was very small and not considered, and should not affect the topography. All the terrain maps are produced as multi-band FITS files. The resulting topographic and tilt maps can be split into two categories. Each category is defined by a ground-sample distance:

a. **Global**: A global map contains information of the entire surface of either Dimorphos and Didymos in a single file. Global maps are provided in several resolutions, from ~2.3 meters down to ~0.15 meters. Global maps are distinguished by a "_g_" near the beginning of the filename, indicating it is a global product.
b. **Site-Specific**: A site-specific map of the DART impact point is a local map with a footprint of 50 x 50 meters or less. The site-specific maps have ground sample distance of 5 cm. These maps are distinguished by a "_l_" near the beginning of the filename, indicating it is a local/site-specific product.

2. **Global Digital Terrain Models** – A global terrain model of the surface of Dimorphos. Such models will be delivered, with as a few ~12000 triangular plates and as many as ~3+ million triangular plates specified by their vertices in Cartesian coordinates with units of km, where each triangular plate has an average plate dimension ranging from ~2.3m for the 12000 facet model to ~0.15m for the ~3 million facet model. The global digital terrain model is produced in the OBJ format.
3. **Asteroid Center of Figure** –The location of the center of figure of a body relative to its center of mass. The DART spacecraft data alone will not be able to determine this parameter for Dimorphos. All products for Dimorphos will have the same center of figure and mass. The shape model of Didymos, as well as the local topographic maps will all be produced relative to the center of mass. The location of the center of figure relative to its center of volume is reported in the text header of the OBJ formatted shape model.
4. **Asteroid Coordinate System** - The coordinate system of Dimorphos and Didymos. This is defined by the location of the prime meridian for these asteroids and their poles. The Dimorphos and Didymos Coordinate System documents describe how these are identified using appropriate IAU procedures. The Didymos and Dimorphos SPICE PCK capture much of the needed information. (see: urn:nasa:pds:dart.spice:spice_kernels).
5. **Asteroid Pole Location, Wobble and Rotation Period** – A single SPICE PCK file containing the radii values, body-fixed frame definition and rotation constants (including pole orientation, and rotation rate both before and after impact) derived by the DART investigation and navigation teams for both Didymos and Dimorphos. These data are already available at SPICE NAIF node. (see: urn:nasa:pds:dart.spice:spice_kernels).
6. **Asteroid Volume** –This data is captured in the text header of the asteroid OBJ file. This is achieved in a straightforward manner through volumetric integration of the shape model.
7. **DART impact location** – This is a simple text entry in an ascii file describing the latitude, longitude and x, y, z location of the DART impact point, determined while registering images to the Dimorphos shape model.
8. **Adjusted spacecraft pointing and trajectory data** – SPICE CK and SPK kernels that have been adjusted on the basis of the best-fit solution determined during SPC processing, which allowed estimating the impact location. These data are already available at NAIF PDS in the DART collection (see: urn:nasa:pds:dart.spice:spice_kernels).

4.3. Data Processing

All derived data processing is performed at Johns Hopkins Applied Physics Laboratory DART SOC. DRACO and LUKE images are received by the SOC via the DART MOC. The processing presented below is completed at the SOC as part of the DART Proximity Working Group workflow.

4.3.1. Data Processing Level

Table 2 shows the data processing levels of all science data products described by this SIS. Correlation to NASA and CODMAC data processing levels and definitions can be found in Section 7.2

Table 2. Data Processing Levels

Derived Data Products	NASA Product Level	DART Processing Level	Description
Global and Impact-Site Specific Topographic and Tilt Maps	Level - 3	L3	Topographic and Tilt maps of the surface of Dimorphos and Didymos.
Global Digital Terrain Models	Level - 3	L3	Models of the shapes of Dimorphos and Didymos.
Asteroid Centers of Figure	Level - 3	L3	Dimorphos and Didymos centers of figure.
Asteroid Coordinate Systems	Level - 3	L3	Coordinate System of Dimorphos and Didymos with prime meridian designated.
Asteroid Pole Locations, Wobbles and Rotation States	Level - 2	L3	Dimorphos' and Didymos' poles and rotation data.
Asteroid Volumes	Level - 2	L3	Didymos' and Dimorphos' volumes
DART Impact Location	Level - 2	L3	DART impact location

4.3.2. Data Product Generation

The DART Proximity Working Group (PWG), members of the DART investigation team, will collect and/or produce all the products described in this SIS as part of the SOC process at JHUAPL. These will be stored at the DART SOC prior to delivery to the NASA PDS.

The generation of global and impact-site-specific digital terrain models is an iterative process leading to products of increasing fidelity. We deliver two versions of these products: an initial version with lower fidelity, and a final version with higher fidelity. In both cases, the products possess identical formats. The next paragraphs describe how the derived data sets are produced and then delivered to the PDS.

Initially, all the DRACO images of the surfaces of Dimorphos and Didymos are taken to create a shape model of the asteroid using stereophotoclinometry (SPC; Gaskell et al., 2008; Gaskell 2011; Barnouin et al. 2020; Craft et al. 2020). As LICIACube images become available, these data get added to the shape model solution generated with SPC.

SPC combines stereo techniques with photoclinometry to derive the tilt of an asteroid's surface. This shape modeling technique estimates surface tilts at each pixel of a given image by initially using stereo parallax, and a photometric function, to constrain a relationship between a surface's tilt and observed albedo. With this relationship in hand, the tilts of a piece of asteroid surface imaged at multiple emission and incidence angles can be obtained via least-squares that best duplicates the input images. Once the surface tilts are obtained, the geometric height across each map can be determined by integrating over the tilts in a logical manner. These individual terrain maps (called "maplets") of the surface can then be joined together to produce global and local digital terrain models. SPC processing includes the use of asteroid limb and terminator data to initially constrain the shape of an asteroid. For more details on SPC processing see Daly et al., 2023; Gaskell, 2011; Gaskell et al., 2008, 2023; Palmer et al., 2022; Weirich et al., 2022).

In the case of DART, where images provide only limited stereo, the PWG will also take advantage of shape constraints from lightcurve data collected by DRACO and Earth-based telescopes. These lightcurve data aid in estimating the rotation state of Dimorphos, as well as its pole location.

The resulting global and local digital terrain products are the key SPC products that are delivered to the PDS. SPC, with the aid of the lightcurve data, will provide the volumes of Dimorphos and Didymos. SPC alone provides adjustments to spacecraft position and pointing, as well as the impact location of the DART spacecraft.

With surface terrain models in hand, we compute height or geopotential topography as defined on Earth, at the center of facets of any shape model, or global and site-specific maps. Such a definition of topography requires not only a shape model, but also a reference geoid, an estimate of the local geopotential and local acceleration due to gravity (Turcotte and Schubert, 1986). The shape model provides a volume over which to integrate to obtain the surface geopotential, acceleration due to gravity and thus topography for the case of uniform density. For the DART products, we assume uniform density because the data collected are of insufficient quality to identify density heterogeneity within Didymos and Dimorphos.

Products of topography, potential, gravity and slope will be generated assuming uniform gravity. The PWG uses the Werner and Scheeres (1996) technique to compute the geoid and gravitational acceleration of an asteroid. We have adapted the algorithm to include the effects of Didymos (considered a point source) on Dimorphos. Using this algorithm, we compute the scalar potential U at each facet center of a shape model, and the associated vector of acceleration due to gravity $\boldsymbol{g}$.

Once a geoid is computed, the height or topography e as measured at each facet center x of a shape model or at each OLA return becomes $e = [U(x)-U_{ref}]/|\boldsymbol{g}|$ where U_{ref} is a reference potential. Because of the important centrifugal effects due to the rotation of Didymos, we set U_{ref}

to the minimum potential at the surface rather than some other average value. Because Dimorphos is a slow rotator, we set U_{ref} to an area averaged potential value. This still does not remove the effect of Didymos' gravity on Dimorphos and tends to provide difficult to interpret values of e for Dimorphos. To compute surface slope θ in degrees with respect to gravity, we use $\cos\theta = \boldsymbol{n}(x).\boldsymbol{g}(x)/|\boldsymbol{n}(x)||\boldsymbol{g}(x)|$ where $\boldsymbol{n}$ is the normal vector to each facet center x of a shape model produced and $\boldsymbol{g}$ is the gravity vector.

We will also provide various measures of surface tilts. Tilts are a measure of surface shape that are independent of geopotential topography. If provided for a global model, these include:

1. Tilt β (magnitude) and Tilt direction α (azimuth): Tilt β of each facet of a shape model is provided relative to the radial vector $\boldsymbol{R}$ to that facet center. It is computed using $\cos\beta = \boldsymbol{n}(x).\boldsymbol{R}(x)/|\boldsymbol{n}(x)||\boldsymbol{R}(x)|$. The direction α of this tilt is determined by projecting the normal vector $\boldsymbol{n}$ into a plane that lies parallel to the pole of the asteroid, but is perpendicular to the x and y components of $\boldsymbol{R}$. The clock angle in degrees of this projected vector, clockwise from the +z-axis, then becomes α.
2. Average tilt β_{avg}, Average tilt direction α_{avg}, Tilt standard deviation β_{std}, and Tilt direction standard deviation α_{std}: This is the average of the tilts surrounding a given facet x, within a user-defined ellipse that surrounds this facet. The radial vector R_x of the central facet x used in calculating the average tilt for all the facets within the ellipse. To avoid areal biases due to the size of facets surrounding x, this tilt is normalized by the area of each tilt projected into the plane defined by the average normal $\boldsymbol{n_{av}}$ across all the facets within the prescribed ellipse. The angle α_{avg} is the average direction of the tilt angles also area normalized. The clock angle in degrees of this projected vector $\boldsymbol{n_{av}}$ then becomes α_{avg}. The angle β_{std} is a measure of the standard deviations of Tilt across the prescribed ellipse, while α_{std} provides a measure of the standard deviation of tilt directions across the ellipse. These two values are also area averaged. These are simple measures of surface roughness at a given baseline defined by the size of the facets used in the global shape model.
3. Relative tilt L, and Relative tilt direction l: This is the tilt of a facet at a given point x relative to the local average tilt, determined over all the facets within a user defined ellipse that surrounds the facet x. To avoid areal biases due to the size of facets surrounding x, the local average tilt is normalized by the area of each tilt projected into the plane defined by the average normal $\boldsymbol{n_{av}}$ across all the facets within the prescribed ellipse. The angle l is the average direction of the tilt angles also area normalized.

The various tilt values computed for the local impact site model (GSD <15 cm) differ in some instances relative to the global ones:

1. Tilt β_l and Tilt direction α_l: Tilt β_l of each facet in local shape model is provided relative to the central radial vector $\boldsymbol{R_c}$ of the local region. It is computed using $\cos\beta_l = \boldsymbol{n}(x).\boldsymbol{R_c}(x)/|\boldsymbol{n}(x)||R_c(x)|$. The direction α_l of this tilt is determined by projecting the normal vector $\boldsymbol{n}$ into a plane that lies parallel to the pole of the asteroid, but is perpendicular to the x and y components of $\boldsymbol{R}$. The clock angle in degrees of this projected vector then becomes α.
2. Average impact tilt β_{iavg}, Average impact tilt direction α_{iavg}, Tilt standard deviation β_{lstd}, and Tilt direction standard deviation α_{lstd}: This is the average of the tilts surrounding a

given facet x, with a radius r surrounding this facet. In the case of the DART mission, we provide results using r equal to both the size of the spacecraft bus or spacecraft with extended solar panels. In the case of the impact tilt, the impact vector $\boldsymbol{V}$ is used in this calculation rather than radial vector to the facet center as was done for β_l and α_l. To avoid areal biases due to the size of facet surrounding x, this tilt is normalized by the area of each tilt projected into the plane defined by the average normal $\boldsymbol{n_{lav}}$ for the entire local region. The angle α_{iavg} is the average direction of the tilt angles also area normalized. The angle β_{lstd} is a measure of the standard deviations of tilt across r, while α_{lstd} provides a measure of the standard deviation of tilt directions across r. These two values are also area averaged.

3. Relative tilt L, and Relative tilt direction l: This is the tilt of a facet at a given point x relative to the average tilt, determined over all the facets within a user defined ellipse that surrounds the facet x (usually the size of the spacecraft bus or spacecraft with extended solar panels in DART's case). To avoid areal biases due to the size of facets surrounding x, the average tilt is normalized by the area of each tilt projected into the plane defined by the average normal $\boldsymbol{n_{lav}}$ across all the facets within the prescribed ellipse. The angle l is the average direction of the tilt angles also area normalized.

4.3.3. Data Flow

Each shape model (found in separate collections) is built up in an iterative process first with DRACO images and later with LICIAcube images. Information on the pole orientation is obtained from telescopic data; updates to the coordinates are derived after assessing the spacecraft images. The images from DRACO and LICIACube are directly ingested into the SPC from the SOC data repository. NAIF SPICE data (which include some of the preliminary pole information) are accessed via a SPICE metakernel maintained by the SOC. Data products generated by PWG are then returned to the SOC data repository for storage, and then ancillary products (topography, slope, tilts, etc.) are built. The PWG accesses both DRACO and LICIAcube data, as well NAIF SPICE data, through the SOC website. The sizes of the products are shown in Table 3.

Table 3. Altimetry Data Products/ Approximate Volume by Mission Phase

Mission Phase	Commissioning	Cruise	Approach	Terminal	Final
Impact-Specific Topographic and Tilt Maps (MB)	N/A	N/A	NA	NA	604
Impact-Specific Digital Terrain Model (MB)	N/A	N/A	NA	NA	78

Mission Phase	Commissioning	Cruise	Approach	Terminal	Final
Global Topographic Maps (MB)	N/A	N/A	N/A	N/A	17575
Global Digital Terrain Model (MB)	N/A	N/A	N/A	N/A	917
Asteroid Center of Figure (MB)	N/A	N/A	N/A	N/A	<1MB
Asteroid Volume (MB)	N/A	N/A	N/A	N/A	<1MB
Asteroid Coordinate System (MB)	N/A	NA	N/A	N/A	1MB

It is possible that more than one version of these shape (digital terrain) model products may be produced once final data products have been completed. This is not intended to be routine but may occur if one or more calibration or ancillary data files need to be updated. Any changes to the derived data processing component are configuration controlled. Re-processed data products are identified in the filename (see Section 4.3.4) and are noted in product quality note as to why reprocessing was necessary.

4.3.4. Labeling and Identification

The shape (digital terrain) model will be named according to the following conventions, using all lower-case characters in the filename:

Target+"_" +Coverage Type + "_" + Ground Sample Distance+ "mm"+ "_"+ Source/Processing Type + "_" + Description + "_" +"Center Location"+ "_" + "v" + Version + "." + PDS Type

The Coverage Type will be:
- g → for global
- l → for local (regional). Used for both global tileset and site specific products.

The Ground Sample Distance (resolution) is four digits expressed in millimeters plus the appended units indicator of mm.

The Source/Processing Type is one of:

SPC → Product generated using stereophotoclinometry

The Description legend is as follows:

obj → Global or local shape model.
dtm → FITS file that contains a complete set of DTM planes.
For the ancillary FITS files, the description refers to the values that are stored in the binary FITS table. A value is provided for each plate in the corresponding OBJ or DTM file. Section 5.2.1.4, Table 6 contains the Description string for the different ancillary products.

The Target description provides the name of the asteroid for which the product is provided:

dimorphos-> Dimorphos
didymos -> Didymos

An example of the file naming convention is:

dimorphos_l_0320mm_spc_dtm _1000n21000_v001.fits

where 1000N represents latitude of 10.00N, 210.00 represents 210.00 East longitude and 0320mm is for 320-mm gsd. This product was generated using stereophotoclinometry for target asteroid Dimorphos. The DTM means it is a plane-relative DTM. 'v001' is the product version number without decimal points.

4.3.5. 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. DART archive products and documents conform to the PDS4 1.20 Information Model. Prior to public release, all data products will have passed both a data product format PDS peer review and a data product production pipeline PDS peer review to ensure compliance with applicable standards.

4.3.6. Time Standards

Given that products described in this SIS are all derived, date and time of creation of this product in UTC format will be provided. Time Standards used by the DART mission conform to PDS time standards.

4.3.7. Coordinate Systems

All coordinate systems used by the DART mission conform to IAU standards. A complete discussion of the coordinate systems and how they are deployed in the mission can be found in the two documents describing the coordinate systems for Didymos and Dimorphos referenced in Section 2.

4.4. Data Validation

All software is configuration controlled and any changes made follow a SOC Configuration Control Plan, which includes testing of changes.

In addition to software types of verification and validation, each DART data product has been peer reviewed for both PDS data format acceptability and scientific usefulness. No changes are expected to data formats after a complete peer review.

5. Detailed Data Product Specifications

The following sections provide detailed data product specifications for shape (digital terrain) models generated by the DART project. These specifications provide sufficient detail for data product users to read and interpret the products.

5.1. Data Product Structure and Organization

The DART Mission archive is organized into bundles for each spacecraft (DART and LICIACube), the DART telescopes, and the DART Shape Models. SPICE NAIF products are directly delivered to NAIF under a DART SPICE bundle and are not part of this shape model bundle.

The DART shape (digital terrain) models are formatted either as binary tables, FITS DTM files, or shape files (OBJ). The binary tables, which store ancillary data such as surface slope and gravitational potential, are stored in FITS format with metadata stored in the FITS header and the table stored as a FITS binary table extension. The binary tables are also referred to as ancillary files. The FITS DTM files are stored in FITS image format with metadata stored in the FITS header and the image cube stored as a three-dimensional image. The image cubes may also be referred to as FITS Image Cubes. The derived data bundle is broken down by shape model collection.

The data are organized into collections as follows:

data_derived_dimorphos_model_v003
data_derived_dimorphos_model_v004
data_derived_didymos_model_v003

where the shape model is identified by the shape model target and version number. Thus, dimorphos_model_v004 is not an updated version of dimorphos_model_v003 it is a different shape model altogether. Higher version numbers are typical of higher quality.

5.2. Data Format Descriptions

5.2.1. Digital terrain maps, Topography and Tilt Maps

The DART SOC provides digital terrain maps in two formats, OBJ and FITS (image cubes). The formats, described in the following paragraphs, are similar for both impact-site-specific and global products. The FITS headers and ancillary file headers are also similar for both types.

The OBJ file format is described in Section 5.2.1.1, and the formats of the ancillary files that accompany the OBJ files are described in 5.2.1.3.

5.2.1.1. OBJ

The digital terrain models are provided as plate models of the terrain of Didymos or Dimorphos, in the form of a series of triangular plates. The data format is the OBJ format (which is a special-case ASCII Table) that is allowed by the PDS and is commonly used to describe 3-dimensional shapes. A detached XML file that is PDS compliant will precede this file. See Section 5.2.3 for an example of the file format.

5.2.1.2. FITS Image Cubes

This file is a three-dimensional image cube, with the first two axes being location on the surface and the third axis a series of planes that hold data associated with each location on the surface. The first six planes in every image cube will always be latitude, longitude, radius, x, y, z position, in that order. All other planes are specified by the PLANEn keyword, which defines the contents of the n^{th} plane. Descriptions of the data types contained in a given PLANEn can be found in Section 5.2.2. These files have a detached XML label.

Two products are available: (1) A single site-specific file produced for analyses of the impact site on Dimorphos only. In this product the impact is at the center of the provided DTM. (2) Global files that can be used for analyses of the entire surface of either Dimorphos and Didymos. The global product is a simple map where the entire surface of Didymos or Dimorphos are cut up into latitudinal and longitudinal grids that contains the entire surface of the asteroid in a single product.

Table 4 shows the headers and keywords used for FITS image cubes. All keywords are present in impact-site-specific and global FITS headers unless otherwise stated. Keywords that are used only for the site specific and global tilesets are marked with a bold "**DOES NOT EXIST IN GLOBAL FITS HEADER"** and these do not apply for the Global Fits Image Cube files. If a specfic value is not available at the time when the product is generated, it is set to -999.0

Table 4 – Example Header for FITS Image Cube

Keyword	Value Examples values given	Description
SIMPLE	T	Conforms to FITS Standard
BITPIX	-32	8 unsigned int, 16 & 32 int, -32 & -64 IEEE floating point
NAXIS	3	Number of axes: 3 for global and local DTMs
NAXIS1	1024	Number of positions along axis 1 of data cube
NAXIS2	1024	Number of positions along axis 2 of data cube
NAXIS3	4 to 45	Defines number of data planes within each data cube, where each position in axis 3 corresponds to a new data type (e.g., 'Height', 'Albedo', 'Sigma',

		'Quality') as specified in the PLANEn keyword records. There are currently 32 planes defined, including the first six location planes.
EXTEND	T	FITS dataset may contain extensions
COMMENT	Header Information	
HDRVERS	'1.0.0'	The version number of this FITS header. Value is a string.
COMMENT	Mission Information	
MISSION	'DART	Mission: DART
HOSTNAME	'DART'	PDS Terminology
TARGET	'DIMORPHOS'	Target Object: 'DIMORPHOS' / 'DIDYMOS'
ORIGIN	'DART SOC'	DART Science Operations Center
Comment	Identification Info	
MPHASE	'Final'	Mission Phase; Likely to be made up of cumulative data Final phase only. Assume phase marked is latest used to make SPC product
Comment	Shape Data Source	
DATASRC	'SPC'	Source of shape model data – likely SPC
DATASRCF	'ZS1664.MAP'	Source data filename. Useful for traceability or for debugging. Set to 'multiple files' if more than one source file was used to create the product. Value is a string. **Only for site specific maps.**
DATASRCV	'DALYv20'	Name and version of SPC model employed. Value is a string.
DATASRCD	'2022-10-28T14:04:22'	Creation date of SPC model employed. Value is a string of format: 'YYYY-MM-DDTHH:MM:SS' in UTC.
OBJ FILE	'dimorphos_l_00320mm_spc_obj_6000s18000_v101.obj'	Name of associated OBJ shape model file.
Comment	Processing Information	
PRODNAME	'dimorphos_l_00320mm_spc_dtm_6000s18000_v101.fits'	Product Name. Value is a string.

DATEPRD	'2022-10-30T08:12:23'	The date that the DTM was produced. Value is a string of format: 'YYYY-MM-DDTHH:MM:SS' in UTC.
SOFTWARE	'SPC, DART-pipeline'	Name of software used to create map data
SOFT_VER	1	Version of software
Comment	Map Specific Information	
MAP_NAME	'Digital Terrain Model'	Map data type. Will always be 'Digital Terrain Models' for DTM fits files.
MAP_VER	'2.5.1'	Product version number. This will distinguish different generations of the data, on the assumption that models are regenerated with different parameters, different processing sequences). Value is a string.
MAP_TYPE	'Global'	Global or local map.
GSD	320.1	Ground sample distance. Units are provided in comments (e.q. [mm]). For global products, this is the approximate ground sample distance of the DTM at the equator. Value is a real floating point number with format F18.1
Comment	Summary Spatial Information	
CLON	180.0004358715384	Planetocentric longitude of center of local DTM. For global DTM it is set to 0.0. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360, units are degrees.
CLAT	-60.000162623627425	Planetocentric latitude of center of local DTM (deg). For global DTM it is set to 0.0. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is −90 to 90, units are degrees.
LLCLNG	154.0352020263672	Longitude E of lower left corner of DTM. Units are provided in the associated comment immediately

		following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360, units are degrees.
LLCLAT	-36.919944763183594	Latitude of lower left corner of DTM. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90, units are degrees.
URCLNG	247.9739990234375	Longitude E of upper right corner of DTM. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360, units are degrees.
URCLAT	-66.94854736328125	Latitude of upper right corner of DTM. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90, units are degrees.
LRCLNG	203.72459411621094	Longitude E of lower right corner of DTM. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360, units are degrees.
LRCLAT	-35.842166900634766	Latitude of lower right corner of DTM. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90, units are degrees.
ULCLNG	111.4999771118164	Longitude E of upper left corner of DTM. Units are provided in the associated comment immediately

		following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360, units are degrees.
ULCLAT	-69.61784362792969	Latitude of upper left corner of DTM. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90, units are degrees.
CNTR_V_[XYZ]	123.43929	The three coordinates of the vector (on three lines for _X, _Y and _Z) from the center of object to the center of the DTM in body-fixed coordinates. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. **DOES NOT EXIST IN GLOBAL FITS HEADER**
UX_[XYZ]	-23.5672	The three components (of the unit vector (on three lines for _X, _Y and _Z) lying on the reference plane along axis 1 of FITS file, in body-fixed coordinates. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. **DOES NOT EXIST IN GLOBAL FITS HEADER**
UY_[XYZ]	255.0223	The three components of the unit vector (on three lines for _X, _Y and _Z) lying on the reference plane along axis 2 of FITS file, in body-fixed coordinates. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number **DOES NOT EXIST IN GLOBAL FITS HEADER**

UZ_[XYZ]	19.2322	The three components of the reference plane unit normal vector (on three lines for _X, _Y and _Z). This vector is orthogonal to the reference plane and has a positive dot product with CNTR_V. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. **DOES NOT EXIST IN GLOBAL FITS HEADER**
Comment	Plane Information	
PLANEn	'Elevation'	Data plane description. This value must be specified for all data planes 1 through NAXIS3. One keyword for each plane, e.g. PLANE1, PLANE2, PLANE3, etc. All planes values are described in Section 5.2.1.4. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a string
Comment	Product Specific Keyword	
DENSITY	2670	Bulk density of asteroid used to compute gravitational terms. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[kgm^-3]). Value is a real floating-point number.
ROT_RATE	3.3116576167064E-4	Rotation rate of body used to compute gravitational terms. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[kgm^-3]). Value is a real floating-point number.
REF_POT	-53.75446080677394	Reference potential (or geoid) of asteroid in J/kg. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[J/g]). Value is a real floating-point number.

TILT_MAJ	25	Semimajor axis of ellipse over which mean tilt and standard deviation of tilts was determined. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. -999 if not used.
TILT_MIN	25	Semiminor axis of ellipse over which mean tilt and standard deviation of tilts was determined. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. -999 if not used.
TILT_PA	0	Position angle of ellipse over which mean tilt and standard deviation of tilts was determined. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. -999 if not used.
END		Conforms to FITS standard.

The planes of data in the DTM FITS file format can contain heights above the reference plane, albedo, sigma-point data, one of various data quality measures (one for each height and albedo value), and multiple other parameters. All data planes provide values on a grid of locations defined on a reference plane, but also provide the location in the body-fixed asteroid reference frame. The reference plane location in body-fixed asteroid coordinates for local DTMs is specified by its center, CNTR_V, and its orientation in body-fixed asteroid coordinates is specified by a pair of orthogonal unit basis vectors, UX and UY, both lying in the reference plane. The UZ vector is a unit vector normal to the plane, also specified in body-fixed asteroid coordinates. The UX, UY, and UZ unit vectors are for a right-handed coordinate frame. Additional information on the location of the corners of the DTMs are provided.
The number of points on the grid in the UX and UY directions are given by the NAXIS1 and NAXIS2 keyword records, respectively, and the center grid point $\left(\left\lfloor\frac{\text{NAXIS1}}{2}\right\rfloor, \left\lfloor\frac{\text{NAXIS2}}{2}\right\rfloor\right)$ is at a 3D point specified by the CNTR_V keyword record (where the grid indices range over $0, \dots, \text{NAXIS1} - 1$ and $0, \dots, \text{NAXIS2} - 1$, respectively). The grid point spacing along both the UX and UY axis is given in the GSD keyword record. The data are ordered as specified in the FITS standard, and the first and second grid indices increase along the directions specified by the UX and UY keyword records.

For example, the height data $H(x, y)$ is ordered:

$H(0,0), H(1,0), H(2,0), \ldots H(\text{NAXIS1}-1,0), H(0,1), H(1,1), H(2,1) \ldots, H(\text{NAXIS1}-1, \text{NAXIS2}-1)$.

Any or all of the data plane types described above can be included in the DTM file format, so for the n^{th} plane in a particular file, the header of the file will contain a PLANEn keyword record whose value is a string indicating the content of the corresponding plane. The valid values of this string and descriptions of the data plane types are given in Section 5.2.1.4

5.2.1.3. Ancillary Files

The ancillary files are binary tables that follow the FITS standard (data-block size, header format, keyword names, etc.) and provide metadata for the associated OBJ plate model. These are only provided for the *global models* and not each local site map; the local dtm's possess much of the same information in an easier to use format. The ancillary files contain primary and secondary headers (see Table 5) and then six or ten columns for scaler and vector data, respectively. The first four columns are facet number and then the latitude, longitude, and radius of the center of the facet. Facet numbers are listed in order. For scaler data types, there are another two columns, and they contain the data value and its error for that facet. For vectors, there are six more columns that contain, in order, the first vector component, its error, the second component, its error, the third component, and its error. In most cases, an ancillary file corresponds to a plane in the FITS image cube, as shown in Table 6.

The VECTOR RADIUS (vrt string descriptor) ancillary file is an exception to the description above. In addition to the same initial for columns (facet number, latitude, longitude, and radius), it has the XYZ vector and uncertainty (sigma) for each of the three vertices that define the facet. Three facets with three components, each, and with uncertainties for each makes a total of 4+18=22 columns. The sigma columns each follow their data column. Note that ancillary files where tilts are computed over a region of interest, the size of the regions is identified via a TILT keyword. This keyword is not present in all products. In addition, when the keyword for a reference or impact (REF_V_[X,Y,Z]) vector is present, it means that products was computed using this vector rather (see Section Table 7 for additional information). This happens to be the case for the local impact site product, when mean tilt or mean tilt direction is computed.

The following table shows the structure of the header in the ancillary (FITS) files.

Table 5. FITS headers for ancillary files

Keyword	Value Example values given	Description
SIMPLE	T	Conforms to FITS Standard
BITPIX	8	
NAXIS	0	Number of axes; 0 for table
EXTEND	T	Extensions are permitted

Keyword	Value Example values given	Description
COMMENT	Header Information	
HDRVERS	1.0.0	The version number of this FITS header. Value is a string.
COMMENT	Mission Information	
MISSION	‘DART’	Mission: DART
HOSTNAME	‘DART’	PDS Terminology
TARGET	‘DIDYMOS’	Target Object
ORIGIN	‘DARTSOC’	DART Science Operations Center
Comment	Identification Info	
MPHASE	‘FINAL’	Mission Phase; Likely to be always FINAL for DART. Assume phase marked provides latest data used to make SPC product
Comment	Shape Data Source	
DATASRC	‘SPC’	Source of data – SPC shape model
DATASRCV	‘DALYv20’	Name and version of SPC model employed. Value is a string.
DATASRCD	‘2022-10-29T14:04:22’	Creation date of SPC model employed. Value is a string of format: ‘YYYY-MM-DDTHH:MM:SS’ in UTC.
OBJ_FILE	dimorphos_g_00320mm_spc_obj_0000n00000_v101.obj	Name of parent OBJ file for which the data in this ancillary file corresponds. Value is a string.
Comment	Processing Information	
PRODNAME	dimorphos_g_00320mm_spc_slp_0000n00000_v101.fits	Product File Name. Value is a string. Example is a slope file.
DATEPRD	‘2022-10-31T08:12:23’	The date that this MAP product was produced. Value is a string of format: ‘YYYY-MM-DDTHH:MM:SS’ in UTC.
SOFTWARE	SPC, DART-Pipeline	Name of software used to create map data
SOFT_VER	1	Version of software
Comment	Map Specific Information	
MAP_NAME	slope	Map data type. Indicates parameter mapped to the facets of the surface of an OBJ file with the same base name (e.g.,

Keyword	Value Example values given	Description
		l_00320mm_spc_obj_9000s28978_v101.obj for this example fits header).
MAP_VER	2.5.1	Product version number. This will distinguish different generations of the data, on the assumption that models are regenerated with different parameters, different processing sequences. Value is a string.
MAP_TYPE	'local'	Global or local map.
GSD	320.1	Ground sample distance. Units are provided in the associated comment immediately following the forward slash in square brackets ([mm]).
Comment	Summary Spatial Information	
CLON	145.1234568	Longitude E of center of local DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360, units are degrees.
CLAT	-22.1234567890123	Latitude of center of local DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90 degrees. Units are degrees.
LLCLNG	93.1234567890123	Longitude E of lower left corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360. Units are degrees.
LLCLAT	-23.12345679	Latitude of lower left corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90. Units are degrees.

Keyword	Value Example values given	Description
URCLNG	193.1234567890123	Longitude E of upper right corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360. Units are degrees.
URCLAT	-23.1234567901233	Latitude of upper right corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90. Units are degrees.
LRCLNG	193.1234567890123	Longitude E lower right corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0 to 360. Units are degrees.
LRCLAT	-23.1234567901233	Latitude lower right corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90. Units are degrees.
ULCLNG	193.1234567890123	Longitude E upper left corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is 0-360. Units are degrees.
ULCLAT	-23.1234567901233	Latitude upper left corner of DTM (deg). Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number with the format F18.13. Range of values is -90 to 90. Units are degrees.
CNTR_V_[XYZ]	-123.343929901233	The three coordinates of the vector (on three lines for _X, _Y and _Z) from the center of object to the center of the DTM in asteroid body-fixed coordinates. Units are provided in each keyword's associated comment immediately following the

Keyword	Value Example values given	Description
		forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. **DOES NOT EXIST IN GLOBAL FITS HEADER**
UX_[XYZ]	-23.5671290901233	The three components (of the unit vector (on three lines for _X, _Y and _Z) lying on the reference plane along axis 1 of NFT fits file, in asteroid body-fixed coordinates. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. **DOES NOT EXIST IN GLOBAL FITS HEADER**
UY_[XYZ]	-255. 671290901233	The three components of the unit vector (on three lines for _X, _Y and _Z) lying on the reference plane along axis 2 of NFT fits file, in asteroid body-fixed coordinates. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number **DOES NOT EXIST IN GLOBAL FITS HEADER**
UZ_[XYZ]	-19.2671290901233	The three components of the reference plane unit normal vector (on three lines for _X, _Y and _Z). This vector is orthogonal to the reference plane and has a positive dot product with CNTR_V. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number. **DOES NOT EXIST IN GLOBAL FITS HEADER**
REF_V_[XYZ]	-123. 671290901233	The three coordinates of the reference or impact vector (on three lines for _X, _Y and _Z) that is used when this vector is used to define tilts over a region of interest. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[m]). This keyword is present only for local mean tilt and mean tilt direction products. Value is a real floating-point number.

Keyword	Value Example values given	Description
		DOES NOT EXIST IN GLOBAL FITS HEADER
Comment	Product Specific Keyword	
DENSITY	-2670.	Bulk density of asteroid used to compute gravitational terms. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[kgm^-3]). Value is a real floating-point number.
ROT_RATE	-3.31E-04	Rotation rate of body used to compute gravitational terms. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[kgm^-3]). Value is a real floating-point number.
REF_POT	-53.75446080677394	Reference potential (or geoid) of asteroid in J/kg. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[J/g]). Value is a real floating-point number.
TILT_MAJ	12.5	Semimajor axis of ellipse over which mean tilt and standard deviation of tilts was determined. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number.
TILT_MIN	12.5	Semiminor axis of ellipse over which mean tilt and standard deviation of tilts was determined. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a real floating-point number.

Keyword	Value Example values given	Description
TILT_PA	0.0	Position angle of ellipse over which mean tilt and standard deviation of tilts was determined. Units are provided in the associated comment immediately following the forward slash in square brackets (e.g., /[deg]). Value is a real floating-point number.
End		
Primary Data Unit		None as per FITS Standard
Secondary Header		
XTENSION	‘TABLE’	This is the binary Ancillary table of data values per shape model facet
BITPIX	8	
NAXIS	2	Dimensionality of Table
NAXIS1	81 or 164	Dimensionality of Table
NAXIS2	‘49152’	Number of facets
PCOUNT	0	No group data
GCOUNT	1	One group
TFIELDS	6 or 10	Number of fields in table
TTYPE1	FACET_NUM	Shape Model Facet number
TFORM1	I10	Format
TBCOL1	2	Column offset
TTYPE[2,3,4]	‘LAT, LON, RADIUS-coordinate’	The type of value stored in the first (for Latitude, second for Longitude, and third for Radius)

Keyword	Value Example values given	Description
		column of the file. This will be the Latitude [or Longitude, Radius] coordinate in the body fixed frame of the center to each facet of the OBJ file defined by the MATCHOBJ record keyword. Units are provided in each keyword's associated comment immediately following the forward slash in square brackets (e.g., /[m]). Value is a string.
TFORM[2,3,4]	1E	Format
TBCOL[2,3,4]	13, 30, 47	Column offset
TFORM[5; optionally 6,7]	1E	Format
TBCOL[5; optionally 6,7]	64,[81,98]	Column offset
TTYPE[5; optionally 7,9]	'SLOPE'	The type of values stored in the fourth column of this file. In some instances, for vector quantities, this will include two additional columns for Y and Z values. The units will be specified in added note.
TFORM[6 or 6,8,10]	1E	Format
TBCOL[6 or 6,8,10]	47 or 115,132,149	Column offset
TTYPE[6; optionally 6,8,10]	'SIGMA'	The type of values stored in fifth (or eighth to tenth) column of data. This value is an estimate of the uncertainty associated with each value in the column defined by the TTYPE[5 and optionally 6,7] keyword. Error analysis is used to propagate uncertainties when these are not directly measured. Values of zero or NaN in certain areas of a model usually mean that there was no data in those areas of the shape model. The units will be specified in added note. All type of data used is defined in DSIG_DEF keyword.
END		
Secondary Data Unit		Binary Table

5.2.1.4. Data Description

This section describes the types of data included in the Shape (Digital Terrain) model bundle and how to identify the product files. Table 6 shows the relationship between the planes (PLANEn) in the image cubes, the names of the columns (TTYPE keyword) in the ancillary files, the three-letter string appended to ancillary files to identify them, and the descriptive string (MAP_NAME keyword) used in the headers of the ancillary files to identify them. N/A indicates that the given plane or ancillary file does not exist.

Data for a given plane in the FITS image cubes are identified by value associated with the FITS keyword 'PLANEn', where 'n' is an integer going from 1 to the number of planes in the image cube. The 'n' value also indicates the location of the plane in the image cube, n=1 is the first plane in the cube, n=2 is the second, and so on.

Data contained in the Ancillary FITS is identified by the MAP_NAME keyword in the header and by the Description portion of the filename string (Section 4.3.4). The TTYPE FITS keyword, which identifies each column of the FITS table, will also contain a string describing the data column.

Table 7 provides additional information on each type of data.

Table 6. Data Type Identifiers

PLANEn (Image Cube) Evaluated at vertex	TTYPE Data Column (Ancillary File) Evaluated at facet centers	Units	Description String (Ancillary Filename)	MAP_NAME (Ancillary File)
Latitude	LATITUDE	degrees	N/A	N/A
Longitude	LONGITUDE	E degrees	N/A	N/A
Radius	RADIUS	km	N/A	N/A
X Coordinate	N/A	km	N/A	N/A
Y Coordinate	N/A	km	N/A	N/A
Z Coordinate	N/A	km	N/A	N/A
Height above plane normal	N/A	km	N/A	N/A
Sigma	Sigma (see Table 7)		N/A	N/A
Albedo	ALBEDO	unitless	alb	albedo-intensity*
Quality	N/A		N/A	N/A
Normal vector X	NORMAL VECTOR_X	km	nvf	normal vector
Normal vector Y	NORMAL VECTOR_Y	km	nvf	normal vector
Normal vector Z	NORMAL VECTOR_Z	km	nvf	normal vector
Gravity vector X	GRAVITY VECTOR_X	m/s^2	grv	gravity vector
Gravity vector Y	GRAVITY VECTOR_Y	m/s^2	grv	gravity vector
Gravity vector Z	GRAVITY VECTOR_Z	m/s^2	grv	gravity vector
Gravitational magnitude	GRAVITATIONAL_MAGNITUDE	m/s^2	grm	gravitational magnitude
Gravitational potential	GRAVITATIONAL_POTENTIAL	J/kg	pot	gravitational potential
Elevation	ELEVATION	m	elv	elevation
Slope	SLOPE	degrees	slp	slope
Facet tilt	FACET TILT	degrees	fti	facet tilt
Facet tilt direction	FACET TILT DIRECTION	degrees	fdi	facet tilt direction
Mean tilt	MEAN TILT	degrees	mti	mean tilt
Mean tilt direction	MEAN TILT DIRECTION	degrees	mdi	mean tilt direction
Tilt variation	TILT VARIATION	degrees	tiv	tilt variation
Tilt direction variation	TILT DIRECTION VARIATION	degrees	div	tilt direction variation
Relative tilt	RELATIVE TILT	degrees	rti	relative tilt
Relative tilt direction	RELATIVE TILT DIRECTION	degrees	rdi	relative tilt direction
Max relative height	MAX RELATIVE HEIGHT	km	mht	max height/depth within an ellipse
Area of each facet	Area	km^2	are	facet area

*Albedo is not available in the local or global dtm fits files

The following table provides more information on data types. The data types are identified using the MAP_NAME column, if possible, otherwise they are identified by the PLANEn name. Data types that appear in the FITS image cube and in the ancillary file are defined as measured “at the point of interest”. The point of interest in an ancillary file is the center of the facet and the point of interest in an image cube is the pixel, where a pixel corresponds to a vertex of a given facet in the associated shape model.

The tilt data types are evaluated within an ellipse centered at the point of interest. The ellipse semimajor and semiminor axes and the ellipse position angle define the ellipse footprint at each point of interest. The semimajor axis is described by the TILT_MAJ keyword, the semiminor axis by the TILT_MIN keyword, and the position angle by the TILT_PA keyword. All three keywords define the 'tilt ellipse' mentioned in the descriptions for the tilt data.

Table 7. Data Descriptions

Data Type	Description
Latitude	Planetocentric latitude at vertex (FITS image cube) or facet center (ancillary file) (deg)
Longitude	Planetocentric longitude at vertex or facet center (deg)
Radius	Radius of vertex or facet center (km). Unlike latitude and longitude, radius is a calculated or measured parameter and has an uncertainty. This uncertainty is in a separate plane (keyword 'Sigma') for image cubes and in the sixth column of a separate ancillary file (FACET_CENTER_RADIUS) for OBJs.
X,Y,Z coordinate	X, Y, Z coordinate of the vertex for image cubes (km).
Albedo	For SPC products, contains albedo from SPC with values between 0 and 2 and a mean value of 1. The SPC values are the average of the relative surface reflectance at the given grid point computed from all images in which the grid point is visible.
Sigma	For the FITS image cube, the sigma plane contains for SPC a best estimate of the standard deviation of the vertex measured along each vertex vector, derived from past experience. For ancillary files, the TTYPE-sigma column is the uncertainty associated with the data column. The DSIG_DEF keyword describes the uncertainty metric. Note when this value is 0.0 it is likely because there was just a single or no imaging or altimetry data provided at that given location.
Quality	Measurement of quality. For SPC products, a number between 1 and 5 will be provided for each map pixel showing how well the images used SPC satisfy the SPC imaging requirements: namely 1 image in each of the 4 cardinal directions, and 1 albedo images all within the necessary GSD for the map resolution.
normal vector	X, Y, Z coordinate of the normal vector to the point of interest in the body-fixed asteroid reference frame (unit vector).
gravity vector	X, Y, Z coordinate of the acceleration due to gravity at the point of interest in the body-fixed reference frame. (m/s^2)
gravitational magnitude	Magnitude of the gravitational acceleration on the surface at the point of interest. The magnitude of the gravitational acceleration in initial used to compute this parameter assumes uniform density for the asteroid (given by DENSITY keyword) and takes into account the rotation rate of the asteroid (given by ROT_RATE keyword). (m/s^2) For Dimorphos, we also take into account the effect of Didymos. If deemed necessary, the influence of Dimorphos on Didymos will also be included.

gravitational potential	Gravitational potential on the surface at the point of interest. (J/kg)
elevation	Elevation or topography of the surface where the local geoid and gravity field is taken into account. High elevations are equivalent to mountains, while low elevations are valleys. A fluid on the surface would move from high elevation to low. Elevations in DART products are the result of assuming uniform density for the asteroid (given by DENSITY keyword) and take into account the rotation rate of the asteroid (given by ROT_RATE keyword) (m) For Dimorphos, we also take into account the effect of Didymos. If deemed necessary, the influence of Dimorphos on Didymos will also be included.
slope	Slope relative to gravity at the point of interest in the body fixed asteroid reference frame. The slope in initial DART products is the result of assuming uniform density for the asteroid (given by DENSITY keyword) and take into account the rotation rate of the asteroid (given by ROT_RATE keyword). (deg) For Dimorphos, we also take into account the effect of Didymos. If deemed necessary, the influence of Dimorphos on Didymos will also be included.
height above plane normal	Height of point of interest above a plane fit to all of the points in the (local) shape model. Measured along the vector normal to the plane. (**ONLY IN LOCAL IMAGE CUBE**)
facet tilt	Magnitude of the tilt of the surface at the point of interest in the body-fixed asteroid reference frame. The tilt is defined as the angle separating the normal from the radial vector to the point of interest.
facet tilt direction	Tilt direction at the point of interest. This angle is defined as the clockwise angle of the normal vector from the +z axis of the asteroid after the normal vector has been projected into the plane defined by the x,y component of the radial vector to the point of interest.
mean tilt	Area averaged tilt within a tilt ellipse centered at the point of interest. Uses impact vector REF_V_[X,Y,Z] when supplied for computing the tilts.
mean tilt direction	Direction of the area averaged tilt. Defined as the clockwise angle of the mean normal vector from the +z axis of the asteroid after this normal vector is projected into the plane defined by the x,y component of the radial vector or the impact vector REF_V_[X,Y,Z] when supplied, to the point of interest.
tilt variation	The variation of the tilt within the tilt ellipse centered at the point of interest.
tilt direction variation	The variation of the tilt direction within the tilt ellipse centered at the point of interest.
relative tilt	Magnitude of the tilt relative to the local average tilt determined via a tilt ellipse centered at the point of interest.
relative tilt direction	Direction of the relative tilt. Defined as the clockwise angle of the mean normal vector from the +z axis of the asteroid after this normal

	vector is projected into the plane defined by the x,y component of the radial vector to the point of interest.
facet area	Area of the facet.
sigma of vertex vector	X, Y, Z components and the SIGMA of each component for the three vertices that define a facet. Only exists as ancillary file and, with 22 columns, is the only ancillary file that does not have either six or ten columns. If 0.0, there was no meaningful statistical data available at the given point.
Max height/depth within an ellipse	Max height/depth within a tilt ellipse (km)

5.2.2. Asteroid Digital Terrain Model

This section describes ASCII OBJ files of vertex coordinates followed by facet designations used for representing an asteroid shape in 3D.

The DART digital terrain models describe a Dimorphos or Didymos shape model as a series of triangular plates. The data is in the OBJ format that is allowed by the PDS and is typically used in many fields of research to describe three-dimensional shapes. It consists of a series of vertices, followed by a listing of facets, which define how the prior vertex descriptions combine to make individual facets. Vertex coordinates are Cartesian, in the coordinate system defined above with the origin at the center of mass, the +z axis along the direction of the smallest moment of inertia nearest the right-handed rotation axis, the +x axis passing through the Prime Meridian, and the +y axis defined in a right-handed sense. Dimensions are km. This file is in ASCII Table format preceded by a detached xml label file (*.xml). The DART digital terrain model OBJ files include a comment section at the top of the ASCII file, where each comment line begins with '#'. This section includes a description of what is found in the OBJ file, and basic statistics about the shape model as appropriate for a global versus impact-site-specific file. The data included in this comment includes information on the volume of the asteroid and the location of the center of figure (CENTROID) as required in section 4.2.

An example of the starting lines of a DART OBJ follow:

```
#Model of the surface of Dimorphos. File consists of vertices and facets. Facets are triangular and
#connected by the right hand rule. The components of the vertices in the data table follow the
#letter 'v' in the first part of the file. The number of each vertex is defined by the position
#of the vertex in the list defined by the letter 'v', where the first line in this list is the first vertex.
#In the second half of the file, the three numbers following the letter 'f' are the vertex numbers
#that make up each facet.
#MISSION = DART
#TARGET = Dimorphos
#ORIGIN = DARTSOC
#MPHASE = Final
#DATASRC = SPC
#DATASRCV = DALYv20
```

```
#SOFTWARE= 'SPC,ALT-pipeline'  \ Software used to create map data
#SOFT_VER= '2021-Jun-19'       \Version of software used to create map data
#MAP_NAME='Digital Terrain Model' \Product name
#MAP_VER = '0.0.2   '          \Product version number
#MAP_TYPE= 'global  '          \ Defines whether this is a global or local map
#GSD     =              8440.0 \ [mm] grid spacing in units/pixel
#COMMENT summary spatial information
#CLON    =                 0.0 \ [deg] longitude at center of image
#CLAT    =                 0.0 \ [deg] latitude at center of image
#LLCLNG  =               180.0 \ [deg]
#LLCLAT  =               -90.0 \ [deg]
#URCLNG  =               180.0 \ [deg]
#URCLAT  =                90.0 \ [deg]
#LRCLNG  =               180.0 \ [deg]
#LRCLAT  =               -90.0 \ [deg]
#ULCLNG  =               180.0 \ [deg]
#ULCLAT  =                90.0 \ [deg]
#Number of Plates          = 3072
#Number of Vertices        = 1538
#Number of Edges           = 4608
#Euler Polyhedron Formula   = 2
#Surface Area              = 0.08674324469614840   km^2
#Plate Area Mean           = 2.823673329952746e-05 km^2
#Plate Area Min            = 2.189296074843742e-05 km^2
#Plate Area Standard Dev    = 3.011747566250398e-06 km^2
#Edge Length Mean          = 0.008438248698654756  km
#Edge Length Max           = 0.01207486664557377   km
#Edge Length Variance       = 2.234008644910798e-06 km^2
#Surface Closed?           = Yes
#Volume                    = 0.002308071031887155  km^3
#Centroid [km]:
#  [2.2363293637937105E-19, -1.9305065448133738E-19, -1.2873229286453539E-18]
#Moment of Inertia Tensor Relative To Origin [kg km^2]:
#  [4.984473727276177E-6, -2.3822801641527198E-23, -1.0257039595657543E-23]
#  [-2.3822801641527198E-23, 7.011321767498426E-6, -1.3234889800848444E-24]
#  [-1.0257039595657543E-23, -1.3234889800848444E-24, 7.920416631506854E-6]
#Moment of Inertia Tensor Relative To Centroid [kg km^2]:
#  [4.984473727276177E-6, -2.3822801641527198E-23, -1.0257039595657543E-23]
#  [-2.3822801641527198E-23, 7.011321767498426E-6, -1.3234889800848438E-24]
#  [-1.0257039595657543E-23, -1.3234889800848438E-24, 7.920416631506854E-6]
#Principal Axis 0
#  [0.0, 1.2212453270876722E-15, -1.0]
#Principal Axis 1
#  [0.0, -0.9999999999999999, -1.1657341758564144E-15]
#Principal Axis 2
#  [1.0, 0.0, 0.0]
#Extent [km]:
```

```
#  X: [-0.10400000214576721, 0.10400000214576721]
#  Y: [-0.07999999821186066, 0.07999999821186066]
#  Z: [-0.06650000065565109, 0.06650000065565109]
#Model has 3072 facets.  This satisfies f = 3*4^n with n = 5.
#Model has 1538 vertices and 3072 facets.  This satisfies v = f/2+2.
#0 vertices have duplicates
#0 unreferenced vertices found
#0 zero area facets found
v  -0.0529100000858307   0.0463999994099140   0.0423099994659424
v  -0.0483699999749661   0.0424299985170364   0.0471299998462200
v  -0.0453800000250340   0.0485000014305115   0.0442200005054474
v  -0.0560799986124039   0.0403599999845028   0.0448400005698204
v  -0.0508500002324581   0.0363099984824657   0.0495399981737137
v  -0.0586499981582165   0.0343700014054775   0.0469000004231930
v  -0.0528399981558323   0.0301900003105402   0.0514900013804436
v  -0.0606999993324280   0.0284599997103214   0.0485399998724461
v  -0.0544099994003773   0.0240899994969368   0.0530200004577637
…

f          1          502        2
f          2          502        503
f          2          503        3
f          3          503        504
f          3          504        4
f          4          504        505
f          4          505        5
f          5          505        506
f          5          506        6
f          6          506        507
f          6          507        7
f          7          507        508
...
```

Each face is numbered by its ordinal position in the list of Face Definitions

5.2.3. Asteroid Center of Figure

ASCII text table describing the planetocentric x, y and z offsets of the location of the center of figure of each asteroid in meters relative to each asteroid's center of mass. This is achieved in a straightforward manner by computing the asteroid's spatial centroid through a volumetric integration.

Data Type – ASCII table file with three numbers.

Field:

X-coordinate of centroid (center of figure) relative to center of mass (km),
Y-coordinate of centroid (center of figure) relative to center of mass (km),
Z-coordinate of centroid (center of figure) relative to center of mass (km)

5.2.4. Asteroid Coordinate System

The asteroid coordinate system of Dimorphos is defined in part by the location of the prime meridian for Didymos. A geological feature that will be associated with this prime meridian will be determined by the DART team after impact and will be placed in the two documents describing the coordinate systems for Didymos and Dimorphos referenced in Section 2. The document includes:

1. A reference to the version of global shape model and DRACO/LICIACube images used to define the coordinate system
2. Prime Meridian Feature Descriptions for Didymos and Dimorphos
3. Pole Descriptions and best-fit ellipsoid dimensions for both Didymos and Dimorphos
4. A reference to the relevant pole orientation kernel (PCK) that was used to define the two coordinate systems (see DART SPICE archive at the NAIF node).

5.2.5. Pole Location, Wobble and Rotation State

Pole Location, Wobble and Rotation state data will be formatted as NAIF SPICE PCK files and maintained at the DART SPICE archive at the NAIF node. Note that PCK files use IAU poles, where North is defined as being above the invariable plane of the Solar System, opposite to the +z direction in the asteroid coordinate system.

Data Type – ASCII file

Fields:

BODY920065803_RADII=vector defining the three longest axis of the asteroid

BODY920065803_POLE_RA = defines the right ascension (RA) of Dimorphos' pole, and first order and second order time dependence of declination

BODY920065803_POLE_DEC=defines the declination (DEC) of Dimorphos' pole, and first order and second order time dependence of declination vector defining the declination (DEC) of asteroid pole

BODY920065803_PM = values defining the location of asteroid prime meridian in days past J2000

920065803 is the NAIF ID assigned for Didymos. 120065803 is assigned to Dimorphos.

5.2.6. Asteroid Volume

This is computed in a straightforward manner through volumetric integration. The only data required is a shape model for the asteroid. This information is located in the header of each global shape models OBJ file.

Data Type – ASCII table file with one number.

Field: Volume (km^3)

5.2.7. Adjusted spacecraft pointing and trajectory data

The spacecraft pointing and spacecraft trajectory will be provided as NAIF SPICE kernels, CK and SPK, respectively. These have the identical format as the source CK and SPK that are provided by the navigation and spacecraft teams, but the data are adjusted to reflect the realignments required to reduce the errors and data-mismatches in the DTMs. These usually have the name SPC in their name. These kernels are located in the DART archive of the NAIF node.

5.3. Label and Header Descriptions

Each product of the DART Shape Model Bundle has an associated detached PDS4 compliant XML label. This label contains enough information for a user to understand and interpret the data product and the circumstances of data collection.

Many of the DART Shape Model data products are FITS files with associated FITS headers, as described in section 5.2. The headers are keyword = value in format and comply with the FITS standard. Header information includes mission, timing, geometry and input file specific information. The ASCII OBJ files also possess similar information in a comment section at the beginning of their files. The information contained in the header is duplicated in the detached PDS XML label.

6. Applicable Software

6.1. Utility Programs

At the current time, the DART project has no plans to release any mission specific utility programs. FITS files can be viewed in any FITS compatible utility program.

6.2. Applicable PDS Software Tools

The PDS supplies a number of software tools that can be used in conjunction with PDS data products. Please refer to the PDS4 software website (http://pds.nasa.gov/pds4/software/index.shtml) for additional information on these tools

6.3. Software Distribution and Update Procedures

As the DART project will not be providing software, this section is not applicable.

7. Appendices

7.1. Acronyms

Phrase/Acronym	Description
AAS	American Astronomical Society
AIAA	The American Institute of Aeronautics and Astronautics
ASCII	American Standard Code for Information Interchange
CODMAC	Committee on Data Management and Computation
DART	Double Asteroid Redirect Test
DTM	Digital Terrain Model/Map
ELV	Elevation relative to gravity
FITS	Flexible Image Transport System
GRM	Magnitude of surface gravity
GRV	Gravity vector
GSD	Ground Sample Distance
IAU	International Astronomical Union
IEEE	Institute of Electrical and Electronics Engineers
LICIACube	Light Italian Cubesat for Imaging of Asteroids
LUKE	LICIACube Unit Key Explorer
MB	MegaBytes
MOC	Mission Operations Center
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
OBJ	Object file format
PCK	Planetary Constants Kernel
PDS	Planetary Data System
SIS	Software Interface Specification
SOC	Science Operations Center
SPC	Stereophotoclinometry
SPICE	NASA's observation geometry information system developed and maintained by NAIF. SPICE acronym comes from Spacecraft ephemeris (SPK), Planetary constants (PCK), Instrument (IK), Camera-matrix (CK), and Events (EK)
UTC	Coordinated Universal Time
XML	Extensible Markup Language

7.2. Definitions of Data Processing Levels

Table 8 shows the comparison of DART, NASA and CODMAC data processing levels.

Table 8. Definition of data processing levels for science data (DART/DRACO, PDS4, NASA & CODMAC)

DART/ DRACO	PDS4	NASA	CODMAC	Description

	Packet Data	Packet Data	Raw Level 1	Telemetry data stream as received at the ground station, with science and engineering data embedded.
Raw Images	Raw Data	Level 0	Edited Level 2	Instrument science data (e.g., raw voltages, counts) at full resolution, time ordered, with duplicates and transmission errors removed. Prior to PDS4, referred to as Experiment Data Records (EDRs).
	Partially Processed Data	Level 1A	Calibrated Level 3	NASA Level 0 data that have been located in space and may have been transformed (e.g., calibrated, rearranged) in a reversible manner and packaged with needed ancillary and auxiliary data (e.g., radiances with the calibration equations applied). Prior to PDS4, referred to as Calibrated Data Records (CDRs) and in some cases Derived Data Products (DDPs).
Calibrated Images	Calibrated Data	Level 1B	Resampled Level 4	Irreversibly transformed (e.g., resampled, remapped, calibrated) values of the instrument measurements (e.g., radiances, magnetic field strength). Prior to PDS4, referred to as either Derived Data Products (DDPs) or Derived Analysis Products (DAPs).
		Level 2	Derived Level 5	Geophysical parameters, generally derived from NASA Level 1 (CODMAC level 3 and 4) data, and located in space and time commensurate with instrument location, pointing, and sampling. Prior to PDS4, referred to as Derived Analysis Products (DAPs).
Shape Model data files	Derived Data	Level 3	Derived Level 5	Geophysical parameters mapped onto uniform space-time grids. Prior to PDS4, referred as derived analysis products (DAPs).
Calibration Files Image Backplanes		Level 4	Ancillary Data Level 6	Non-science data needed to generate calibrated or resampled data sets and consisting of instrument gains, and offsets, spacecraft positions, target information, pointing information for scan platforms, etc.

7.3. References

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