Knowledge Inventory of Foundational Data Products in Planetary Science

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Some of the key components of any Planetary Spatial Data Infrastructure (PDSI) are the data products that end-users wish to discover, access, and interrogate. One precursor to the implementation of a PSDI is a knowledge inventory which catalogs what products are available, from which data producers, and at what initially understood data qualities. We present a knowledge inventory of foundational PSDI data products: geodetic coordinate reference frames, elevation or topography, and orthoimages or orthomosaics. Additionally, we catalog the available gravity models that serve as critical datums for the assessment of spatial location, spatial accuracy, and ultimately spatial efficacy. We strengthen our previously published definitions of foundational data products to assist in solidifying a common vocabulary that will improve communication about these essential data products.

Knowledge Inventory of Foundational Data Products in Planetary Science

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Key Points:

- This work identifies over 100 foundational data products for the solar system.
- This work describes criteria for orthoimage and orthomosaic products to be considered foundational.
- Foundational data product metadata, including internal accuracy and interoperability are reported.

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Abstract

Some of the key components of any Planetary Spatial Data Infrastructure (PDSI) are the data products that end-users wish to discover, access, and interrogate. One precursor to the implementation of a PSDI is a knowledge inventory which catalogs what products are available, from which data producers, and at what initially understood data qualities. We present a knowledge inventory of foundational PSDI data products: geodetic coordinate reference frames, elevation or topography, and orthoimages or orthomosaics. Additionally, we catalog the available gravity models that serve as critical datums for the assessment of spatial location, spatial accuracy, and ultimately spatial efficacy. We strengthen our previously published definitions of foundational data products to assist in solidifying a common vocabulary that will improve communication about these essential data products.

1 Introduction

The ultimate goal of a Planetary Spatial Data Infrastructure (PSDI) (Laura et al., 2017) is to have spatial data be discoverable, accessible, and usable by the non-spatial expert; spatial data should just work. The average planetary scientist does not currently have unencumberd access to systems to discover and access homogenized spatial data with reported spatial accuracies and fitness-of-use information without requiring processing which needs spatial expertise. The cost of this processing is non-trival (Malik & Foster, 2012) and numerous terrestrial Spatial Data Infrastructures (SDIs) and clearinghouses have been developed to address these issues (Arctic SDI Working Group on Strategy, 2015; Craglia, 2010; Crompvoets et al., 2004).

Laura et al. (2018) proposed a framework for the development of a PSDI and identified them as an example of a complex adaptive system (e.g. Grus et al., 2010). Those efforts were top-down and described broad functional and organizational requirements for the successful development of a PSDI. A bottom-up approach can be employed (e.g. Rajabifard et al., 2002) where a PSDI is composed of five elements: users, policies, standards, access networks, and data. By adopting this view, we conceptually isolate data as an independent component, and identify those products necessary to bootstrap a PSDI implementation. The first step in creating a data centric view of a PSDI is to understand what data are available.

The creation, development, and retention of institutional knowledge that supports successful operations is a critical activity (van Donk & Riezebos, 2005). A knowledge inventory is a systematic cataloging of the knowledge currently retained within an organization (van Donk & Riezebos, 2005). This information can bootstrap the creation of foudational data products where gaps are identified (Archinal, Laura, Kirk, et al., 2017) and seed geoportals (Maguire & Longley, 2005; Beyer et al., 2018) with rapidly available data in order to drive the development in a user-centric direction.

In this work, we refine existing definitions of foundational data products, and we identify candidate spatial products as foundational data products. In the course of this effort we detail the criteria used to asses whether a product is foundational, describe the methods used to locate these products, and enumerate a body-by-body listing, creating a knowledge inventory.

2 Defining Foundational Data Products

Laura et al. (2017) identify three classes of foundational planetary data products: geodetic coordinate reference frames, topography, and orthoimages. Members of the planetary science community have written abstracts, book chapters, and given presentations seeking to clarify the definition of a planetary foundational data product (e.g. DellaGiustina et al., 2018; Laura et al., 2018; Archinal, Laura, Becker, et al., 2017; Dickson & Ehlmann, 2019).

Laura et al. (2017, 2018) assert that defining a product as foundational is based on two criteria. The first criteria is that foundational data products must facilitate or allow for rigorous spatial error assessment and reporting. In order to apply and draw conclusions from spatial analysis methods one must understand the impact of random and systematic errors in their data sets as these errors propagate through any subsequent analysis. Sources of spatial error must be accounted for in the interpretation of analysis results. Without knowledge of the spatial efficacy of the data, it is quite possible to draw erroneous conclusions using robust statistical methods. The second criteria is that foundational data products must have the widest possible scope of impact across the subset of the planetary sciences making use of spatial data.

The interpretations and conclusions drawn from these observational studies in planetary sciences frequently depend upon the ability to make geographic and geometric comparisons to processes that have been observed terrestrially. Therefore, the accuracy and associated error of the observed information is of critical importance when seeking to draw conclusions. Orthoimages are the only products that are rigorously transformed from direct observations into a geospatial context that maintains accurate spatial relationships. We assert that all other derived products, while of critical importance for some aspects of planetary science, do not have both a scope of impact as deep or broad as the three aforementioned foundational data products and the ability to quantify spatial accuracy to report spatial efficacy.

2.1 Geodetic Coordinate Reference Frame

A defined and agreed upon geodetic coordinate reference is the foundation upon which geospatial analysis rests (Drewes, 2009). The reference frame is a method used to communicate the precise location of something in relation to an agreed upon origin (Archinal et al., 2018).

As described in Laura et al. (2017), the International Astronomical Union (IAU) Working Group on Cartographic Coordinates and Rotational Elements (Archinal et al., 2018) defines the geodetic coordinate reference frame for all major bodies in the Solar System. This includes the definition of North, a prime meridian, and an equator (thereby defining a horizontal datum), as well as the definition of some shape or shape approximation (thereby defining a vertical datum). By adopting the IAU recommendations, communication about spatial locations and spatial relationships is possible because all users are communicating using the same system. We note that gravity models can be stored in a different system (principal axis), but conversion is possible to the broadly used IAU-recommended system. In instances where common geodetic coordinate reference frames are not adopted or are mixed, the potential for unintended spatial errors to occur is significantly increased.

2.2 Elevation

We look to Maune et al. (2007) to tighten the previously provided (Laura et al., 2017, 2018) definitions for foundational elevation data sets. Tightening the definition is critical to avoid confusion in how heights are reported and due to an increased number of missions collect data from small bodies and derive foundational data products, e.g., (Barnouin et al., 2019). Elevation data sets report a series of heights relative to an underlying datum. Three classes of heights are (1) orthometric height, (2) ellipsoidal height, or (3) Cartesian height. Normally, the reported height is the orthometric height, or the distance along a plumb line between some surface point and a defined geoid (Vaníček et al., 2012; Maune et al., 2007). Where the geoid is an equipotential gravity derived surface that is a product of the distribution of mass within the body. On Earth, the geoid approximates mean sea level. Since the geoid is derived from an underlying gravity model the accuracy of the geoid is directly impacted by the knowledge of the underlying density of the surface; even on Earth the densities of the surface are not entirely known (Vaníček et al., 2012). These ellipsoidal heights are the distance, along a perpendicular plumb line, between the surface and a best fit bi- or tri-axial ellipsoid. If the orthometric height (H) and the ellipsoidal height (h) are known, the geoid height (N) can be computed as N = h - H. Finally, Cartesian heights are the distance from a center of mass or center of figure defined origin and a surface point, generally reported as the Z component in a standard 3D Cartesian coordinate system.

Reporting and interpreting heights for small and irregular bodies is more problematic than for large, roughly spherical bodies. First, the accuracy of reported orthometric heights can be significantly impacted by the estimation of a geoid. For small, irregular bodies, assumptions such as uniform density can lead to significant error in the geoid. Additionally, rapid variation in the geoid and potentially non-correlated changes in the already irregular shape can make interpretation of orthometric heights challenging. Second, bi- or tri-axial ellipsoid approximations of the overall shape are not sufficiently accurate to yield comparable heights across the body. Third, the irregular shape of the body also make comparisons of Cartesian heights outside local regions of rough topographic homogeneity non-intuitive. The challenges in creating, interpreting, and using foundational elevation data product for small, irregular bodies have not precluded their creation. Below, we identify elevation data sets reporting orthometric heights that we suspect are being using and interpreted most commonly in local spatial regions, as well as shape models reporting Cartesian heights that we believe are being primarily used for global topography and general shape comparisons.

Once a vertical datum is selected, topographic data (collected using lidar, radar, or derived from Infrared (IR), Near Infrared (NIR), and visible data using photoclinometry, stereophotoclinometry, and/or stereophotogrammetry techniques) can be placed into local, regional, and global contexts. In instances where lidar data are collected, these data frequently become proxy products for the geodetic coordinate reference frame, e.g., Lunar Orbiter Laser Altimeter (LOLA) as the product used to define the lunar geodetic coordinate reference frame.

2.3 Orthoimages

The third kind of foundational data products are orthoimages. Orthoimages are derived from remotely sensed images (IR, NIR, Visible Spectrum (VIS)) that are geometrically corrected for topography and sensor orientation (tilt). Thrower and Jensen (1976) state that '[o]rthopoto-mapping represents a technique by which spatially arrayed data might be both more accurately measures and communicated because of the special attributes of the orthophoto map, namely, the image of an aerial photograph and the metric qualities of a controlled line map'. Orthoimages are planimetrically correct (Greeley & Batson, 2007; Jensen, 2009), and can be used to measure geographic distances, shapes, angles, and areas for features that are independent of topography (Jensen, 2009). An example of a planimetric feature that is frequently considered in the planetary sciences would be an impact crater. The shape, bounding ellipse, angles of orientation along the semi-major axis, or distance between features are all independent of the underlying topography. In fact, removal of topographically induced error is essential to quantify the true geometric properties of the feature.

The accuracy of orthoimages are highly correlated to the accuracy of the underlying DEM or shape model that is used for topographic correction. This is because each pixel of the unrectified image is projected to the surface, a surface elevation is extracted from the DEM, and the pixel value interpolated into the correct value. Errors in the Digital Elevation Model (DEM), or errors in image to DEM co-registration translate into errors in look vector intersection. These errors result in interpolated values that are incorrect. Differences in resolution between image data and topographic data (e.g. a 6 m/pixel image and a 463 m/pixel DEM) result in orthoimages that are only truly orthorectified over the longest wavelength surface features. When assessing orthoimages for accuracy and fitness of use, understanding the accuracy and provenance of the underlying DEM is essential. Data products definable as orthoimages range from those orthrectified to a spherical body representation to those orthorectified to a high resolution DEM.

Occluded features in an image are those which are not visible due to a particular image geometry. In the terrestrial case, orthoimages of urban areas exhibit occlusion when features are blocked by a tall object (e.g. buildings). In the planetary case, occlusion is evident in images with highly oblique observation angles, when image limbs are in view, and on irregularly shaped bodies. A classic orthoimage will either interpolate the occluded areas, resulting in image smear, or fill the unobserved areas with null data. If multiple observations of the same feature are acquired with different viewing geometries, an orthoimage which minimizes these occluded areas can be created.

In addition to supporting robust computation of geographic relationships, orthoimages are also critical for photometry and spectroscopy. Hapke (1981) identifies phase, the angle between the sun and the sensor at a given geographic location (pixel), as impacting observed reflectance spectra. Uncorrected topographic relief directly impacts the shape of the observed reflectance spectra. Accurate topographic and sensor orientation is necessary to help achieve the highest possible accuracy in the observed reflectance spectra.

Orthoimages are essential data products derived from DEMs and remotely sensed image data. The act of orthorectification corrects for relief and sensor orientation induced error in order to have a planimetrically correct, two-dimensional, representation of the observed scene. Orthoimages allow for accurate measurement of distances, morphologies, areas, and geographic relationships. The ability to assess these relationships is a cornerstone to being able to perform accurate assessment of the fitness-for-use of a given data product.

2.4 Gravity Models

Gravity models are not foundational data products themselves, but are an important component in their creation. We include them in our knowledge inventory because accurate gravity models serve to improve the spatial efficacy of all spatial data.

Gravity models acquired via radio tracking (e.g. D. E. Smith et al., 2012, for the case of Mercury) allow for the computation of a geoid. The geoid is an equipotential surface from which accurate radii and by extension an ellipsoidal datum can be extracted. A gravity model significantly improves the accuracy of geodetic coordinate reference frames and derived topography.

2.5 Byproducts of Foundational Data Products

The creation of foundational data products results in the derivation of a number of valuable byproducts. These include: (1) image mosaics, (2) geodetic control networks, (3) updated ephemeris information, and (4) photometric models. These byproducts are valuable for scientific study in and of themselves, quantifying and reporting spatial accuracies, generating or updating foundational data products, or building context during a scientific study.

2.5.1 Image Mosaics

Image mosaics are not foundational data products. Image mosaics can be generated from observations, foundational products, or other derived products. Therefore, the classification of image mosaics is nuanced, and a function of the provenance of the underlying input data. Greeley and Batson (2007) frame and contrast image mosaics (photomosaics in the original texts) with true maps, stating that '[t]hey differ from true maps because photographic images are collections of complicated light and dark patterns related to both illumination and surface coloration and thus do not lend themselves to precise verbal or schematic definitions. Geometrically, they are perspective views...[and] are projections of three-dimensional objects onto two-dimensional image planes.' This description is of images that have been mosaicked with adjacent images to generate a single image of larger spatial extent. Mosaicking non-foundational data products does not result in a foundational data product. Mosaicking foundational orthoimages results in a second-order foundational data product, i.e., a foundational data product that has been derived from existing foundational data products, the underlying orthoimages in this case.

Below, we present a classification scheme for image mosaics to help data users determine whether or not the products they have discovered or created can be considered second-order foundational. To understand the fitness for use of a particular product, it is necessary to understand what potential spatial errors exist, the extent or magnitude of those errors, and the impact of the error on the analysis to be performed. In sum, we consider this the spatial efficacy of the derived product. We identify four contributing components that can be used to assess the spatial efficacy of an image mosaic: (1) geodetic control, (2) reference frame, (3) rectification, and (4) intended use.

Geodetic Control: The methods used to align image mosaics define the classification of then derived product. Image mosaics can be controlled, semi-controlled, or uncontrolled. In order to classify as a controlled mosaic, the sensor positions and orientations of multiple images must have been updated using a rigorous photogrammetric bundle adjustment (described below). The application of bundle adjustment and subsequent updates to the sensor ephemerides results in both improved geographic location on the surface and absolutely quantifiable spatial accuracy. Semi-controlled mosaics can be created by taking the initial, estimated geographic position, and then warping (rubber sheeting or georeferencing) the images on the surface into a position where discontinuities between images are minimized. The resulting products are generally visually quite appealing, but have a limited capacity for spatial accuracy assessment and are unsuitable for cross product error analysis or co-registration with a spatial accuracy requirement. Finally, uncontrolled image mosaics use the initial, estimated geographic location of the images on the surface without any correction for inter-image discontinuities. Uncontrolled image mosaics are well suited for a first look at a geographic region, but care must be taken as the image locations within the scene are approximate.

Reference Frame: A controlled (or semi-controlled) mosaic can be related to the reference frame either relatively or absolutely. A relatively controlled image mosaic 'floats' above the geodetic coordinate reference frame and has not been tied to the broader geospatial context. An absolutely controlled image mosaic has been rigorously tied to a geodetic coordinate reference frame. Therefore, intra-data set evaluations (assuming both products are controlled to the same coordinate reference frame) are possible.

Rectification: The level of rectification applied to the images in the image mosaic also defines the fitness-for-use. As described above, unrectified images are in a perspective view that suffers from topographic and sensor orientation induced errors. Orthorectified images have been topographically corrected for a planimetric view. A rigorously controlled image mosaic that has been rectified to a spherical body representation can suffer from significant topography induced errors that can not be removed simply by controlling the data, and we do not consider such an image or mosaic to be orthorectified without topographic information.

Intended Use: Finally, image mosaics can be classified based upon the way in which the individual pixels or Digital Number (DN) values are being reported. We classify these as either being qualitative or quantitative. In the former, image ordering is selected for cosmetic effect to minimize image boundaries and generate an appealing product to view. Image seams can then be further masked using any number of image processing techniques (e.g., boxcar filtering, gradient domain tonal matching, etc.) Image mosaics for science applications can be generated using a quantitative approach to image ordering, for example by minimizing emission angles and preferring nadir viewing geometries, or by selecting images with the highest spatial resolution. This usage distinction is the least quantitative as the act of deriving an image mosaic requires that some quantity of data are removed from the final product.

Table 1 enumerates the possible permutations given the above classes. We note that uncontrolled image mosaics are neither relatively nor absolutely controlled as the image locations are a best approximation based upon initial sensor position and pointing. Semi-controlled mosaics and relatively controlled image mosaics with orthorectification are potentially suitable products for a wide range of science studies assuming that spatial errors are reported and science uses are resilient to spatial errors at the appropriate spatial scale. Semi-controlled products are not suitable for image co-registration as the errors that propagate through the process are potentially non-linear and quantification is exceptionally problematic. Orthorectification and absolute control operate in conjunction to derive a product with the highest spatial accuracy. The act of absolute control makes co-registration of the image data to the underlying DEM more accurate. The higher co-registration accuracy in the DEM results in higher accuracy orthoimages, and by extension a more accurate image mosaic. Only absolutely controlled, orthorectified image mosaics can be considered foundational data products. An image mosaic meeting these criteria is a second order foundational product as it is derived from the aforementioned foundational data products. In Section 3, below, we identify image mosaics that are derived from foundational data products and image mosaics that are not derived from foundational data products. In the case of the latter, the image mosaics derived from non-foundational data products are the current best available.

2.5.2 Control Networks

Control networks are the collection of tie points identifying common features across two or more images that can be used to photogrammetrically control some number of images (e.g. M. T. Bland et al., 2018). They are not foundational data products. The photogrammetric control process utilizes the points within a control network to update the position, orientation, velocity, and potentially sensor characteristics in order to minimize the 3D pixel reprojection error between all observations of the same point (e.g. Beyer et al., 2018). The result of this process is updated sensor and spacecraft ephemeris information (described below). The publication and distribution of control networks support the iterative refinement of ephemeris information across research teams, co-registration of data across sensors and spacecraft, and robust assessments of accuracy. Sparse control networks have been used as a basis for topographic point densification, subsequent shape model estimation, and DEM derivation (e.g., (K. J. Becker et al., 2016)).

2.5.3 Updated Ephemeris Data

Ephemeris data are the position, orientation, and characteristics of a sensor that allow one to parameterize a sensor model (Laura et al., 2018) and spatialize a recorded value from the sensor to the surface of a body. Through the process of deriving relatively or absolutely controlled images and image mosaics, or through the use of updated ra-

FDP	Control	Reference Frame	Orthorectified	Digital Numbers	Fit-for-Use
No	Uncontrolled	N/A	No	Qualitative	Quick view, not geospatial, errors not quantified
No	Uncontrolled	N/A	No	Quantitative	Quick view, not geospatial, errors not quantified
No	Uncontrolled	N/A	Yes	Qualitative	Quick view, not geospatial, errors not quantified
No	Uncontrolled	N/A	Yes	Quantitative	Quick view, not geospatial, errors not quantified
No	Semi-Controlled	Relative	No	Qualitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful and a product of multiple factors
No	Semi-Controlled	Relative	No	Quantitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful and a product of multiple factors
No	Semi-Controlled	Relative	Yes	Qualitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful and a product of multiple factors
No	Semi-Controlled	Relative	Yes	Quantitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful and a product of multiple factors
No	Semi-Controlled	Absolute	No	Qualitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful and a product of multiple factors, cross instrument errors can be compounding
No	Semi-Controlled	Absolute	No	Quantitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful and a product of multiple factors, cross instrument errors can be compounding
No	Semi-Controlled	Absolute	Yes	Qualitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful, cross instrument errors can be compounding
No	Semi-Controlled	Absolute	Yes	Quantitative	Regional Work, Small Scale (1:500,000+), spatial errors can be meaningful, cross instrument errors can be compounding
No	Controlled	Relative	No	Qualitative	Geospatially enabled, spatial errors can be meaningful, cross instrument work is not possible, inter-data set geometric relationships are clean
No	Controlled	Relative	No	Quantitative	Geospatially enabled, spatial errors can be meaningful, cross instrument work is not possible, inter-data set geometric relationships are clean
No	Controlled	Relative	Yes	Qualitative	Geospatially enabled, cross instrument work is not possible, inter-data set geometric relationships are clean
No	Controlled	Relative	Yes	Quantitative	Geospatially enabled, cross instrument work is not possible, inter-data set geometric relationships are clean
No	Controlled	Absolute	No	Qualitative	Geospatially enabled, cross instrument work possible, geometric relationships are inaccurate
No	Controlled	Absolute	No	Quantitative	Geospatially enabled, cross instrument work possible, geometric relationships are inaccurate
Yes	Controlled	Absolute	Yes	Qualitative	Fully geospatially enabled, spatial errors are quantifiable, cross instrument work possible, change detection possible
Yes	Controlled	Absolute	Yes	Quantitative	Fully geospatially enabled, spatial errors are quantifiable, cross instrument work possible, change detection possible

Table 1. Permutations of qualities for image mosaics. All image mosaics should include rigorous error reporting that drives appropriate fit-for-use statements.

dio tracking, spacecraft ephemeris data are updated. This includes adjustments to the exterior orientation including data acquisition time(s), sensor position and orientation(s) with respect to some datum, and sensor velocities (which are a proxy to time). It is also possible that the derivation of controlled products will result in adjustments to a sensor's interior orientation, such as focal length, optical center, or other sensor characteristics (e.g. M. Robinson et al., 2012; Speyerer et al., 2018). In a planetary context this information is most commonly stored in SPICE kernels (Acton, 1996). Updated ephemerides are invaluable and must be made available to the community as they allow for the accurate spatialization of individual data products and not just the use of derived image mosaics. As an example use case, with updated ephemeris information, one can perform change detection analysis knowing that controlled image data will co-register at some quantifiable accuracy.

2.6 Photometric Models

Domingue et al. (2016) state '[p]hotometric analyses are used to standardize images obtained at a variety of illumination and viewing conditions to a common geometry for the construction of maps or mosaics...'. Accurate photometric models, of particular importance to small bodies research where image data can exhibit rapidly changing incidence and emission angles within a single scene, are necessary to correct illumination in much the same way that accurate topography are necessary to correct for geometric distortion. Photometric models allow for the correction of an image, orthoimage, or orthomosaic to represent viewing from a single observation and illumination geometry. The estimation and application of photometric models requires co-registered image and elevation data for the highest possible accuracy.

3 Knowledge Inventory

Here we enumerate the available foundational data products and gravity models for bodies in the Solar System for which flyby or orbital missions have acquired data. The listing does not include telescopic observations, as they are not generally used to create spatially enabled products. Reported data have been identified using the PDS, the USGS Astropedia search tools, the Japan Aerospace Exploration Agency (JAXA) Data ARchive and Transmission System (DARTS) interface, the European Space Agency (ESA) Planetary Science Archive (PSA), the Chinese National Space Administration (CNSA) Data Archives, the Smithsonian Astrophysical Observatory/ NASA Astrophysics Data System, and reference lists from peer-reviewed publications and conference abstracts.

No accuracy assessments have been performed as part of this work, and all reported internal data quality metrics are drawn from the broader literature, typically the data creator. We report both horizontal and vertical accuracies, when available.

Horizontal and vertical accuracies are reported relative to some agreed upon geodetic coordinate reference frame (horizontal and vertical datum). Therefore, the accuracies reported do no include horizontal and vertical error that exists in the coordinate reference frame proxy. Lunar Reconnaissance Orbiter Camera (LROC)-Narrow Angle Camera (NAC) DEMs, identified below in the Moon section, provide an example of the impact of this nuanced distinction that impacts how the products can and should be used. The LROC-NAC DEMs report a horizontal accuracy of 1.5 meters relative to the LOLA reference frame. As a user of the data product, it is important to understand that the 1.5m horizontal error is relative to the LOLA reference frame and the actual, absolute error that should be considered in analysis would be the 1.5m LROC-NAC DEM error plus the reported 20m LOLA reference frame error.

We are unable to include internal data quality metrics such as attribute or metadata accuracy, semantic accuracy (defined narrowly as an assessment of the correctness for semantic interoperability in data discovery), and logical consistency (the internal consistency of a product), as we have not identified any foundational data producers that are reporting these criteria. We hope that future data custodians (those persons or organizations that take ownership and provide long term maintenance of a data product Laura et al., 2017), will consider assessing and maintaining a full suite of internal data consistency metrics.

Data products with GeoTiff, GeoJPEG2000, or Open Geospatial Consortium (OGC) compliant Web Mapping formats are Geographic Information System (GIS) ready. Products in these formats fulfill our 'spatial data should just work' requirement (Laura et al., 2017). Data in the IMG or IMQ formats and published in a peer-reviewed archive are the highest quality products, but are generally not GIS ready (Laura et al., 2018). Finally, we were unable to provide external data quality metrics because data producers have not reported on the fitness of use or qualitative usability of a given product. In general, we have sought to identify those products which are highly available. By this we mean that the products have been deposited into a long-lived data archive (e.g., the Planetary Data System (PDS), PSA, DARTS) or are broadly available over the internet via some non-archival data portal (e.g., a mission team, university, or even personal website). We have identified unreleased products as those products where the data are not freely available. In some cases, one can request the data from a data creator. In other cases, the data are simply unavailable to the general public. Requestable and unavailable data products have been identified below but we assert that they can not be identified as foundational as they can not be widely used by the broader community.

3.1 Mercury

Data from both the Mariner 10 (Cook & Robinson, 2000) and Mercury Surface Space Environment, GEochemistry, and Ranging (MESSENGER) (Solomon et al., 2007) missions have provided a wealth of data from which a large number of foundational data products have been derived. In Table 2, we identify 21 foundational data products. A radio-tracking-derived gravity model, HgM008 (Genova et al., 2019), and Mercury Laser Altimeter (MLA) derived geodetic parameters (Zuber et al., 2012) define the geodetic coordinates reference and geodetic parameters. It is to this reference frame and the MLA proxy that foundational data products should be registered. The Deutsches Zentrum für Luft- und Raumfahrt (DLR) generated DEMs (Preusker, Oberst, et al., 2017; Stark et al., 2017; Preusker, Stark, et al., 2017; Oberst et al., 2017) report good geometric rigidity to the MLA data suggesting that these products are in alignment with the geodetic coordinate reference frame. The stereoscopically derived global model (K. J. Becker et al., 2016) does not report being constrained by the MLA geodetic coordinate reference frame though Neumann et al. (2016) report differences. Regional DEMs (Fassett, 2016; Manheim et al., 2017) do report, where possible being tied to MLA. Orthoimages generated through the DEM creation process (Manheim et al., 2017) are absolutely controlled to the reference frame when those underlying DEMs make use of MLA ground ties. It is not clear if the global orthorectified products (Murchie et al., 2017) have been tied to the geodetic coordinate reference frame. While we report that the global mosaic products (Murchie et al., 2017) are absolutely controlled and orthrectified, they are at best orthorectified to the global DEM. The resolution disparity between these data sets is greater than 450 m.

We note that the breadth of Mercury orthorectified foundational data products demonstrate the potential explosion in co-registered data sets with quantifiable spatial efficacy when a single geodetic coordinate reference frame is agreed upon and control networks are widely shared. Given the wealth of products, potential exists to focus on quantifying spatial accuracies and other internal quality metrics as well as beginning to co-locate data sets and collect external quality metrics that would be of immense value to the non-spatial expert data user. Finally, we note that mosaicked, orthorectified products exist at a global scale, but a source for individual controlled and orthorectified images in a geospatial format that are readily ingested into a GIS do not appear to be available.

3.2 Venus

We have identified five foundational data products, collected by the Magellan mission (Saunders & Pettengill, 1991) for Venus. The MGNP180U gravity model was created using data from the Magellan and Pioneer Venus Orbiter (A. Konopliv et al., 1999). Using these data a reference geoid has been derived. Additionally, Wieczorek (2015) provide a Venus gravity model built using data derived from Magellan (GTDR3.2), Pioneer Venus, and Venera 15/16 altimetry. This is a degree 719 spherical haromic model avaialble in a plain text format and hosted on both Zenodo and GitHub. Synthetic Aperture Radar (SAR) collected topography (Saunders et al., 1990) that was used to derive near global topography (Ford & Pettengill, 1992). Radar collected Mosaicked Image Data Record (MIDR) data and left-look, right-look products were used to create uncontrolled global mosaic products. Using the currently available data, it appears that the limit of foundational data product creation has been attained.

3.3 Moon

The intense scientific interest in our nearest planetary neighbor has resulted in a large number of current foundational data products with high spatial resolutions and reported accuracies. The GRGM1200A gravity model (Lemoine et al., 2014; Goossens et al., 2016), derived using data from the Gravity Recovery and Interior Laboratory (GRAIL) (Zuber et al., 2013), is the most accurate and well understood planetary geoid (discounting the Earth). Barker et al. (2016) suggest that the LOLA/Kaguya Terrain Camera (TC) derived topography, SLDEM2015, has 'become the reference geodetic framework for the lunar community and has led to the highest resolution and most accurate polar digital elevation models (DEMs) to date.' The gravity model, global LOLA product (Neumann, 2009) and SLDEM2015, with spatial extent between 60 °S and 60 °N (Barker et al., 2016), provide a highly accurate and globally defined horizontal and vertical datum to which all other lunar observations can be controlled. Additionally, the existence and accuracy of these datums can serve to demonstrate the value associated with data collection and derivation of a single, agreed upon geodetic coordinate reference frame.

It is not clear if the Apollo data (Nefian et al., 2009) are tied to the reference frame. The Kaguya TC (Haruyama et al., 2012) are not photogrammetrically controlled and are therefore relatively consistent internally, but not tied to LOLA. Finally, we see conference presentations describing the Chandrayaan-1 Terrain Mapping Camera (TMC) stereoscopically derived DEM (Sivakumar et al., 2012), but have not been able to identify a publicly accessible place to access the data product.

The only absolutely controlled lunar orthomosaics are generated alongside the LROC-NAC DEM products (Henriksen et al., 2017). The LROC team has also generated high quality, but uncontrolled orthomosaics of the Lunar North and South poles (Wagner et al., 2015). We note that these products are likely orthorectified to a LOLA base, so an appreciable scale disparity between the LROC-NAC resolution and LOLA derived topography will exist that impacts the accuracy of the orthorectification process in areas of high relief. Likewise the Kaguya global orthomosaic (Haruyama et al., 2012) and individual orthoimages (Haruyama et al., 2012) are uncontrolled. The orthorectification of the Kaguya TC orthoimages should be quite good as the underlying DEMs are generated using the to-be-rectified source images and are therefore absolutely internally consistent. Finally, we can not classify the LROC-Wide Angle Camera (WAC) product as being absolutely controlled as errors in the data were corrected to subpixel visual accuracy by updating the sensor interior orientation (M. Robinson et al., 2012). Therefore, while the WAC mosaic product is qualitatively of exceptional accuracy, the success of the pseudo-registration is a function of the a priori accuracy of the exterior orientation (spacecraft ephemeris) and the pixel resolution. Likewise, the global Clementine product was registered to the LROC-WAC base (Speyerer et al., 2018) meaning that that product is also not absolutely controlled by the definition we propose above.

3.4 Mars

In recent years Phobos and Deimos have seen a rapid expansion in the number of available foundational data products due to both reprocessing of older data (Ernst et al., 2015; Ernst, Gaskell, et al., 2018) and the derivation of new products using Mars EXpress (MEX) High Resolution Stereo Camera (HRSC) data. Phobos is well served with a global control network (albiet unreleased), multiple elevation data sets generated using different methods that allow for cross comparison (R. W. Gaskell, 2011; Wählisch et al., 2010; Ernst, Gaskell, et al., 2018), and a wealth of absolutely controlled image data sets captured by HRSC, Viking Orbiter, Phobos 2, Mars Global Surveyor (MGS), MEX, and Mars Reconnaissance Orbiter (MRO) (Ernst, Gaskell, et al., 2018). Those data sets available via the Small Bodies Mapping Tool (SBMT) (Ernst, Barnouin, et al., 2018) are not also mirrored through another download location for use in a different tool. While less well covered, Deimos has also benefited from the release and reprocessing of older data and is available via the SBMT. Deimos foundational data products include a shape model and collection of absolutely controlled image data products (Ernst, Gaskell, et al., 2018). We have identified the Phobos and Deimos image data (Ernst, Gaskell, et al., 2018) as being absolutely controlled as the spacecraft ephemerides (positions) were updated in order to tie features to the body shape models (personal communication, C. Ernst). As of the writing of this manuscript, the updated kernels have not been released.

Mars currently has the highest number of foundational data products in this inventory. This is due to the number of different flight missions that have collected mapping data, the products that can and have been created using these products, the number of different research teams testing methods for product derivation using the same data sets, and the number of landed missions that require the highest spatial efficacy regional products. The Mars science community is well served with gravity models, a geodetic coordinate reference system proxy in the form of the MGS Mars Orbiter Laser Altimeter (MOLA) (D. E. Smith et al., 1999), the MDIM2.1 control network (Archinal et al., 2001, 2003) and the MDIM2.1 absolutely controlled image mosaic. All three products can and have been used as proxies for the accepted Mars reference frame allowing absolute control of subsequent data sets.

Mars gravity was collected and derived using MGS data (Albee et al., 2001) resulting in numerous iteratively released gravity models including the final MGS95J model (A. S. Konopliv et al., 2006). These gravity data products were then superseded by data collected by the MRO (Zurek & Smrekar, 2007) spacecraft and resulted in the release of the most accurate gravity model to date, the Goddard Mars Model 3 (GMM-3) gravity model (Genova et al., 2016). We also note the incremental release of the Goddard Mars Model 2B (GMM-2B) product that was used as the basis for the MOLA gridded DEM products. These include an interpolated global product at a maximum of 128 pixels per degree, as well as regionally tiled Mission Experiment Gridded Data Records (MEGDRs).

We have identified eight different foundational elevation data products from global to local spatial extents. The MOLA interpolated DEM (Lemoine et al., 2001) and merged HRSC-MOLA product (Fergason et al., n.d.) provide global coverage with areas of interpolation at the poles due to a data gap and larger interpolated gaps, in the case of MOLA, at the equator due to the sensor orbit. While the individual HRSC DEMs are available at 50m per pixel and approximately 44% surface coverage, the merged product is made available at 200m per pixel. At the middle resolutions and spatial extents the Colour and Stereo Surface Imaging System (CaSSIS) (Conway et al., 2018; Re et al.,

2019) sensor on the ExoMars Trace Gas Orbiter spacecraft, HRSC (Gwinner et al., 2010; Dumke et al., 2010; Putri et al., 2019), and MRO Context Camera (CTX) (Fergason et al., 2018; Fergason et al., 2017) sensors have been used to generate regional scale DEMs. We note that the CaSSIS DEMs are, at this time, not available for download or preview. At the highest spatial resolution, the USGS and University of Arizona have generated over 600 High Resolution Imaging Science Experiment (HiRISE) stereoscopically derived DEMs (Kirk et al., 2008; University of Arizona, 2019).

The wealth of Mars elevation data has naturally led to a large number of available orthoimages and orthomosaics. At a global scale, the absolutely controlled MDIM2.1 mosaic (Kirk et al., 2001; Archinal et al., 2003) and semi-controlled CTX mosaic (Dickson et al., 2018) are available. We note that the former is appropriate for follow on control work while the latter, even if georeferenced to MOLA, is not as the image data are semi-controlled; this assessment is inline with that published by the data producer. With a spatial extent from 60 °S to 60 °N the absolutely controlled and orthorectified (to MOLA) THErmal EMission Imaging System (THEMIS) day and night infrared mosaics offer the highest resolution, absolutely controlled orthomosaiced data currently available (Fergason et al., 2013). At more regional scale, more than 1250 HRSC-derived orthoimages (Gwinner et al., 2010) have been generated and released. The orthorectification of these products should be of exceptionally high quality as the scale disparity between the image data (~12.5 m/pixel) and DEM (~50 m/pixel) is small. We note that Mars Quadrangle (MC) 11 has been the focus for automated co-registration (Sidiropoulos et al., 2018) of high resolution visible spectrum data to an HRSC DEM and orthomosaic resulting in the registration of Viking Orbiter, Mars Orbiter Camera (MOC)-NAC, THEMIS-VIS, MRO CTX and MRO HiRISE data (Sidiropoulos & Muller, 2016; Sidiropoulos & Muller, 2016). The MC11 data are available via the iMars web-GISystem (Walter et al., 2017) (personal communication J. Muller).

Also at the regional scale though with much more limited spatial coverage, the USGS-generated, absolutely controlled CTX orthomosaics for landing site analysis are available (Fergason et al., 2017). These products should not be confused with the relatively controlled CTX orthomosaics generated for initial human landing site select work (Hare et al., n.d.). The former are of high spatial efficacy while the latter are 'floating' over the surface and not usable for cross instrument analysis. Finally, the HiRISE-derived DEM products are released with associated orthoimages offering the highest resolution, absolutely controlled Mars data.

3.5 Jupiter

In Table 6, we identify 11 foundational data products across five bodies. Neither Jupiter nor the four Galilean Satellites (Io, Europa, Ganymede, and Callisto) have full gravity models or global topography. Some partial gravity models exist: second degree tidal and rotational parameters for Io (J. D. Anderson et al., 2001), a third degree spherical harmonic model for Europa (J. D. Anderson et al., 1998), an estimate of the spherical harmonics for Ganymede (J. D. Anderson et al., 1996), and the mass and unnormalized quadrupole gravity coefficients for Callisto (J. Anderson et al., 2001). A gravity model for Jupiter has been created (Iess et al., 2018; Buccino et al., 2018) and is presented in Iess et al. (2018) in tabular form. The Jovian system has limited elevation data products available. RAND Corporation generated control networks for Io, Europa, Ganymede, and Callisto (M. Davies et al., 1979), in conjunction with the IAU body definitions, they are the current defacto geodetic coordinate reference frames. Io has the only publicly available topography, a stereoscopically-derived DEM with approximately 75% coverage and one kilometer per pixel equatorial resolution (White et al., 2014).

Images used to create these mosaics were collected by the Galileo Solid State Imager (SSI)(Belton et al., 1992), Voyager 1 (B. A. Smith et al., 1981), and Voyager 2 (B. A. Smith et al., 1979). These were fly-by data acquisition missions. Therefore, the nominal pixel resolution at which a mosaic is being released is not the actual resolution at which images were acquired. For example, the Europa Je 15M CMN controlled photomosaic has a pixel scale between 200m per pixel and 20km per pixel. Therefore, in Table 6, we report pixel ranges for image mosaic resolutions.

3.6 Saturn

We have identified 22 foundational data products for the moons of Saturn (Table 7). These products have been derived from data collected by the recently ended Cassini mission (Matson et al., 2003). We have not identified any gravity models for the Saturnian system though many shape model and stereoscopically derived topography products have been created. These include shape models for Mimas, Enceladus, Tethys, Dione, and Phoebe (R. W. Gaskell, 2013b, 2013d, 2013a). Topography products for Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus have been created (P. Schenk, 2010), but have not been released to the planetary science community. Finally, Titan has been well served with an eighth order spherical harmoinic gravity model and associated geoid (Corlies et al., 2017). Data from Cassini SAR were used to create a spline-interpolated, global elevation product of Titan (Lorenz et al., 2013) at 40km per pixel. Unfortunately, it appears that this product is only available as a publication figure both from the publisher and from the first author's website. Corlies et al. (2017) built upon the original SAR-interpolated topography using data from three sources: (1) SAR-derived topography (Stiles et al., 2009), (2) altimetry data using flight time and nadir viewing geometries (Zebker et al., 2009), and (3) radar-stereophotogrammetrically derived DEMs (Kirk et al., 2012). The resultant product has 8.9% global coverage using non-interpolated sources.

Finally, the DLR has generated a number of semi-controlled, or relatively controlled image mosaics of Mimas (Roatsch et al., 2018), Enceladus (Roatsch et al., 2018), Tethys (Roatsch, Kersten, Matz, Preusker, et al., 2016), Dione (Roatsch, Kersten, Matz, Preusker, et al., 2016), and Rhea (Roatsch, Kersten, Matz, Preusker, et al., 2016). These products, like the Jovian image mosaics, are being released at a nominal scale, but are using flyby data collected across a range of spatial scales. We have identified these as being relatively controlled because they are not using a proxy geodetic coordinate reference frame to assert an absolutely controlled ground location. This is important because none of the aforementioned products include accuracy assessments in the referenced works or alongside the data (in instances where the data are released).

3.7 Uranus

Foundational data products for the Uranian system, Table 8, are limited as mapping data were only collected by flyby observations from the Voyager 1 and Voyager 2 spacecraft. Therefore, we have not identified any gravity models for the reported bodies. RAND Corp generated control networks and the USGS created airbrush photomosaics for Miranda (13 images), Ariel (10 images), Umbriel (6 images), Titania (20 images), and Oberon (5 images). The photo mosaics are available as USGS-generated map sheets in PDF format; these products are not geospatially enabled and ready for use. The control networks have been published online and include the images used to generate them. Unfortunately, software to make use of the networks is not available, therefore these data are also not GIS ready. A user could not independently use the network and update SPICE information to process and project the images in the photo mosaics. We have identified topography products for Ariel, Titania, and Miranda generated using a combination of stereophotogrammetry and photoclinometry near the terminator (P. M. Schenk, 2008). Unfortunately, we have not located a source for these data or associated metadata beyond the figures and text in the abstract.

3.8 Neptune

We have identified three foundational data products for Triton, Table 10. Voyager 1 and Voyager 2 flyby data were used by the RAND Corporation to generate a control network using 57 images of Triton. From these data, a controlled unrectified mosaic was created to the extent of coverage. These data were also used to generate a unreleased DEM using stereophotogrammetry and photoclinometry near the terminator (P. M. Schenk, 2008).

3.9 Pluto and Charon

Foundational data products for Pluto and Charon have been created from data from the recent New Horizons mission (Stern et al., 2015) and are summarized in Table 12. We have not identified any gravity models, but multi-image control networks (unreleased) have been created to control images of the 40% of the surface that was imaged during the flyby (P. M. Schenk et al., 2018b, 2018a). In addition, the creation and adjustment of these networks yielded updated SPICE *spk* and *ck* kernels that support image-wise map projection to the current geodetic coordinate reference frame, these kernels are being prepared for submission to the PDS (personal communication, R. Beyer). The controlled fly-by image data were then used to generate a global (to data coverage) image mosaic, compute body radii, and generate stereophotogrammetric DEMs. Based on the descriptions in P. M. Schenk et al. (2018b) and P. M. Schenk et al. (2018a), we have classified the derived image mosaics as being absolutely controlled and un-rectified.

3.10 Small Bodies

Small bodies reported in this section fulfill two criteria. First, the bodies are not associated, as per the NAIF numbering scheme, to a primary body. Therefore, these bodies all have NAIF identifiers in the 2000000 range. Second, these small bodies have been the target of mapping efforts. The significantly larger collection of Near Earth Objects (NEOs) is not the target of this knowledge inventory and the interested reader could explore the PDS small bodies node, the NASA Jet Propulsion Laboratory (JPL) maintained NHATS database, or the JPLs small-body database browser.

The knowledge inventory, summarized in Table 13, covers asteroids (Ceres, Vesta, Lutetia, Eros, Steins, Itokawa, Bennu, Ryugu) and comets (Borrelly, 67P-CG, 103P/Hartley, and Tempel-1). Each has been served by a mission with instruments capable of creating the three aforementioned foundational data products. The Dawn mission (Russell & Raymond, 2012) captured gravity and imaging data of Ceres sufficient for the derivation of a global gravity model good to 300 km/pixel (A. S. Konopliv et al., 2012; Konopliv et al., 2018), as well as global and regional DEMs of varying spatial resolutions using both stereophotogrammetric methods (Preusker et al., 2016; Jaumann et al., 2017) and stereophotoclinometric (SPC) methods (Park et al., 2019). Using the derived elevation data absolutely controlled, global orthomosaics were created using data from both the High Altitude Mapping Orbits (HAMOs) and the Low Altitude Mapping Orbits (LAMOs) (Roatsch, Kersten, Matz, Preusker, et al., 2016). We note a lack of published accuracy assessments (particular with respect to horizontal errors). The PDS archives 'extras' directory provides geospatial ready GeoTiffs for immediate use in a GIS. Foundational data products derived and made available for Vesta mirror those generated for Ceres with a gravity model (A. Konopliv et al., 2014), stereophotogrammetrically derived DEMs (Preusker et al., 2012; Jaumann et al., 2012), a SPC derived shape model (R. W. Gaskell, 2012), and absolutely controlled orthomosaics (Roatsch et al., 2013; Le Corre et al., 2017).

For Eros, Itokawa, Bennu, Lutieta, Steins, and Ryugu, we have identified a number of elevation products. We have not identified any geodetic coordinate reference frame products (though the elevation products could act as a proxy) or any available orthoimages (whether individual or mosaiced). A SPC shape model for Eros exists in the PDS (R. W. Gaskell, 2008) though we did not locate any error reporting on the product. Likewise, we have found two videos of Structure from Motion (SfM) and SPC-generated shape models of Ryugu in press releases, but have not been able to locate the data (JAXA, n.d.). Finally, a Bennu shape model has been archived in the PDS (Nolan et al., 2013)that includes both horizontal and vertical error reporting. We also note that for many of the asteroid and comet shape models, global imaging in direct sunlight was not possible. Therefore, the global shape models are composite products making use of radar data and feature silhouetting.

For many of the comet shape models, we report the resolution as the number of facets or plates in a given model. Each facet is either a triangle or quadrilateral representing a 'flat' surface. In general, the higher the number of plates the higher the shape model resolution. In instances were the data producers or follow-on papers have reported a nominal ground scale, we have reported this. For example, Jorda et al. (2012) report the nominal ground scale of facets in the Steins SPC derived shape model to be better than 70 meters. For these objects, we see what appear to be orthorectified images as figures in the literature (see any of the referenced comet works), but have not identified sources for these data in an already orthorectified form (i.e., the data user appears to need to orthorectify the images to the available shape information). Therefore, we are not reporting on any available foundational imaging data products beyond those available for Ceres and Vesta.

Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
HgM008	Gravity	N/A	16ppd	Global	Current	IMG	?	GSFC	PDS	Genova et al. (2019)
MLA Derived Geodetic Parameters	Geodetic Coordinate Reference Frame (or Proxy)	?/?	300kmpp	Global	Current	IMG	?	Zuber, et al.	PDS	Zuber et al. (2012)
Mariner 10 Dervied DEM	Elevation	∼20km/?	300kmpp	Regional	Superseded	?	?	Cook et al.	?	Cook and Robinson (2000)
Messenger MDIS Global DEM	Elevation	?/?	64ppd / 655mpp	Global	Current	GeoTiff, IMG, JPEG2000, Cube	?	USGS, APL, Carnegie Science	PDS, USGS	K. J. Becker et al. (2016)
Messenger North Polar MLA Derived DEM V2	Elevation	?/?	250mpp	75N - 90N	Current	IMG, JPEG2000	?	GSFC	PDS	Solomon et al. (2007)
Messenger North Polar MLA Derived DEM V1	Elevation	?/?	2.66kmpp	18S - 90N (Partial)	Partially Superseded	IMG, JPEG2000	?	GSFC	PDS	Solomon et al. (2007)
Messenger DEM H03 Quad	Elevation	45m/30m	220mpp	Quad	Current	IMG, JPEG2000	?	DLR	PDS	Preusker, Oberst, et al. (2017)
Messenger DEM H05 Quad	Elevation	?/35m	220mpp	Quad	Current	IMG, JPEG2000	?	DLR	PDS	Stark et al. (2017)
Messenger DEM H06 Quad	Elevation	55m/30m	220mpp	Quad	Current	IMG, JPEG2000	?	DLR	PDS	Preusker, Stark, et al. (2017)
Messenger DEM H07 Quad	Elevation	?/35	220mpp	Quad	Current	IMG, JPEG2000	?	DLR	PDS	Oberst et al. (2017)
ASU Regional DEMs	Elevation	70-380m/2-255m (See reference)	See reference	Regional	Current	GeoTiff, IMG	?	ASU	PDS	Manheim et al. (2017)

Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
Fassett Regional DEMs	Elevation	50-250m / 10m (See reference)	See reference	Regional	Current	GeoTiff, IMG	?	Fassett, et al.	Webpage ; See Reference	Fassett (2016, n.d.)
Mariner 10 Mosaic	Absolutely Controlled Orthomosaics	$\sim$20km/?	1kmpp	Regional	Superseded	IMG	?	ASU	ASU	M. S. Robinson et al. (1999)
Regional Orthoimages	Absolutely Controlled Orthoimages	70-380m / 2-255m (See reference)	See reference	Regional	Current	GeoTiff, IMG	?	ASU	PDS	Manheim et al. (2017)
Mercury MESSENGER MDIS Global Basemap BDR	Absolutely Controlled Orthomosaic	?/?	256ppd / 166mpp	Global	Current	GeoTiff, IMG	WMS	ACTC	PDS	Murchie et al. (2017)
Messenger Wide Angle Map-Projected Regional Targeted Mosaic	Absolutely Controlled Orthomosaics	?/?	591ppd / 72mpp	Regional	Current	IMG	?	ACTC	PDS	Murchie et al. (2017)
Messenger MDIS NAC/WAC Mosaics (By Mercury Quad / BDR Data)	Absolutely Controlled Orthomosaics	?/?	256ppd / 166mpp	Global	Current	IMG	?	ACTC	PDS	Murchie et al. (2017)
Messenger MDIS NAC/WAC High Incidence Angle East Mosaic	Absolutely Controlled Orthomosaics	?/?	256ppd / 166mpp	Global	Current	IMG	?	ACTC	PDS	Murchie et al. (2017)
Messenger MDIS NAC/WAC High Incidence Angle West Mosaic	Absolutely Controlled Orthomosaics	?/?	256ppd / 166mpp	Global	Current	IMG	?	ACTC.	PDS	Murchie et al. (2017)
Messenger MDIS NAC/WAC Low Incidence Angle Mosaic	Absolutely Controlled Orthomosaics	?/?	256ppd / 166mpp	Global	Current	IMG	?	ACTC	PDS	Murchie et al. (2017)
Messenger MDIS 5-Color Map Projected Multispectral Mosaic	Absolutely Controlled Orthomosaic	?/?	128ppd / 332mpp	Global	Current	IMG	?	ACTC	PDS	Denevi et al. (2016)

Table 2: Twenty-one identified foundational data products for Mercury. Most were created using data collected by the recent Messenger mission, the Mariner 10 mission data were processed into now superseded products.

Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
Magellan MGNP180U	Gravity	NA / NA	1ppd	Near Global	Current	DAT, IMG	?	JPL	PDS	A. Konopliv et al. (1999)
Magellan SAR Altimeter	Elevation	?/50m	22ppd / 5kmpp	Near Global	Current	IMG, GeoTiff	WMS	USGS	PDS, USGS	Ford and Pettengill (1992)
Magellan C3 MIDR Mosaic	Uncontrolled Image Mosaic	?/?	52ppd / 2025mpp	Near Global	Current	GeoTiff	WMS	USGS	PDS, USGS	Ford et al. (1993)
Magellan F-Map Left-look Mosaic	Uncontrolled Image Mosaic	?/?	1408ppd / 75mpp	92%	Current	GeoTiff	WMS	USGS	PDS	?
Magellan F-Map Right-look Mosaic	Uncontrolled Image Mosaics	?/?	1408ppd / 75mpp	55%	Current	GeoTiff	WMS	USGS	PDS	?

Table 3: Four identified Venus foundational data products. All products are radar derived. We have not identified a proxy data set for the IAU defined geodetic coordinate reference frame or a gravity model.

Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
GRGM1200A	Gravity	NA/NA	< 5kmpp	Global	Current	ASCII, GeoTiff, PDS IMG	?	GSFC	PDS	Lemoine et al. (2014); Goossens et al. (2016)
Gridded Lunar Orbiter Laser Altimeter (LOLA)	Elevation	20m/1m	256ppd / 118mpp	Global	Current	PDS3, Cube, GeoTiff	WMS	GSFC	PDS, PDS Annex	Neumann (2009)
SLDEM2015	Elevation	60-100m/3-4m	512ppd / 60mpp	60S to 60N	Current	GeoTiff, IMG, JPEG2000	WMS	GSFC	PDS, USGS	Barker et al. (2016)
Kaguya (SELENE) LALT DEM	Elevation	77m/?	16ppd / 2kmpp	Near Global	Current	IMG	?	JAXA	DARTS	Araki et al. (2009)
Kaguya (SELENE) North Pole LALT DEM	Elevation	77m / ?	16ppd / 2kmpp	79N - 90N	Current	IMG	?	JAXA	DARTS	Araki et al. (2009)
Kaguya (SELENE) South Pole LALT DEM	Elevation	77m / ?	16ppd / 2kmpp	79S - 90S	Current	IMG	?	JAXA	DARTS	Araki et al. (2009)
CLTM-s01	Elevation	445m / 31m	0.25ppd / 7.5kmpp	Global	Superseded	Unreleased	?	CNSA	GRAS	Ping et al. (2009)
CE-1 LAM Derived DEM	Elevation	50m / ?	0.0625ppd / 20mpp	Global	Current	Unreleased	?	CNSA	GRAS	Huang et al. (2018)
GLD100 WAC DEM	Elevation	1km/20m global; 10m flat maria	100mpp	79N - 79SS	Current	GeoTiff, ISIS Cub	WMS	ASU	ASU, USGS	Scholten et al. (2012)
LMMP Generated LRO-NAC DEMs	Elevation	20m / 1 - 2m (reported per product)	1.5mpp	Regional	Current	GeoTiff	?	ASU, USGS,UA, DLR, AMES, OSU	Moon Trek	Tran et al. (2010)
LROC NAC DEMs (>450 created)	Elevation	Varied / Varied (Tied to LOLA)	1.5mpp	Regional	Current	?	WMS	ASU	ASU	Henriksen et al. (2017)
Apollo 15,16, 17 Metric DEM Mosaic	Elevation	91m / 41m	1024ppd	38S - 38N	Current	GeoTiff	?	NASA Ames	PDS	Nefian et al. (2009)

Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
Kaguya TC Stereophotogrammetric DEM	Elevation	50m / 5m	4095ppd / ∼7.5mpp	95%	Current	IMG	?	JAXA	DARTS	Haruyama et al. (2012)
Chandrayaan-1 TMC DEM Mosaic	Elevation	?/?	25m, 10m, 5m(?)	Global (?)	Current	?	?	ISRO	ISDA	Sivakumar et al. (2012); Suresh (n.d.)
LROC WAC Mosaic	Uncontrolled Orthomosaic	45m/?	100mpp	Global	Current	IMG, Cube, GeoTIFF	WMS	ASU	ASU, PDS, USGS	M. Robinson et al. (2012)
LROC NAC DEM Derived Orthomosaics	Absolutely Controlled Orthomosaics	Varies with underlying DEM	1mpp	Regional	Current	IMG	?	ASU	ASU, PDS, MoonTrek	Henriksen et al. (2017)
Uncontrolled LROC NAC Polar Orthomosaics	Uncontrolled Controlled Orthomosaics	Varies with underlying DEM	1mpp	88.5 - 90N/S	Current	Cube	WMS	ASU	ASU	Wagner et al. (2015)
Clementine Mosaic	Uncontrolled Orthomosaics	?/?	250mpp	Global	Current	IMG	WMS	ASU	PDS	Speyerer et al. (2018)
Kaguya TC Global Orthomosaic	Uncontrolled Orthomosaic	50m / 5m	474mpp	Global	Current	GeoTiff	?	JAXA	USGS	Haruyama et al. (2012)
Kaguya TC Orthoimages	Uncontrolled Orthoimages	50m / 5m	4095ppd / ∼7.5mpp	95%	Current	IMG	?	JAXA	DARTS	Haruyama et al. (2012)

Table 4: Twenty identified foundational and non-foundational lunar data products including gravity models, elevation data, and a myriad of orthoimage and orthomosaics products at varying spatial resolutions. We have combined the many foundational regional elevation and orthoimage products into a single entry.

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
401	Phobos	Oberst Control Network	Geodetic Coordinate Reference Frame (or Proxy)	13.7m / ?	N/A	Global	Current	?	?	DLR	?	Oberst et al. (2014)
401	Phobos	Stereo-photoclinometry Derived Shape Model	Elevation	? / ?	15mpp	Global	Current	?	SBMT	Ernst, et al.	SBMT	Ernst et al. (2015)
401	Phobos	Shape Model	Elevation	?/?	60mpp	Global	Superceded	ICQ	?	Gaskell, et al.	PDS	R. W. Gaskell (2011)
401	Phobos	HRSC DEM	Elevation	20m/?	1.9ppd / 100 mpp	Global	Current	GeoTiff, IMG, JPEG2000	?	DLR	USGS, PSA, PDS	Wählisch et al. (2010)
401	Phobos	Viking Global Mosaic	Absolutely Controlled Orthomosaics	?/?	40ppd / 5mpp	Global	Current	GeoTiff	?	Simonelli, et al.	USGS	Simonelli et al. (1993); Stooke (2012)
401	Phobos	HSRC Mosaic	Absolutely Controlled Orthomosaics	20m / ?	16ppd / 12 mpp	Global	Current	GeoTiff, IMG, JPEG2000	?	DLR	USGS, PSA, PDS	Wählisch et al. (2010)
401	Phobos	Co-registered Image Data (>3400)	Absolutely Controlled Orthoimages	?/?	Varies	Global	Current	?	SBMT	Ernst, et al.	SBMT	Ernst, Barnouin, et al. (2018)
402	Deimos	Stereo-photoclinometry Derived Shape Model	Elevation	?/?	?	Global	Current	?	SBMT	Ernst, et al.	SBMT	Ernst et al. (2015)
402	Deimos	Co-registered Image Data (>950)	Absolutely Controlled Orthoimages	?/?	Varies	Global	Current	?	SBMT	Ernst, et al.	SBMT	Ernst, Barnouin, et al. (2018)
499	Mars	Goddard Mars Model 3 (GMM-3)	Gravity	N/A / N/A	120kmpp	Global	Current	Ascii, IMG	?	GSFC	PDS	Genova et al. (2016)
499	Mars	Goddard Mars Model 2B (GMM2B)	Gravity	N/A / N/A	120kmpp	Global	Superseded	Ascii, IMG	?	GSFC	PDS	Lemoine et al. (2001)
499	Mars	MGS95J Model	Gravity	N/A / N/A	120kmpp	Global	Superseded	Ascii, IMG	?	JPL	PDS	A. S. Konopliv et al. (2006)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
499	Mars	Interpolated MOLA DEM	Elevation	100m / 3m	463mpp / 128ppd	Global	Current	IMG, Cube, GeoTiff	WMS	GSFC	PDS, PDS Annex	?
499	Mars	HRSC / MOLA Blended Product	Elevation	100m / 3m	200mpp	Global	Current	GeoTIff	?	USGS	USGS	Fergason et al. (n.d.)
499	Mars	HRSC South Pole DEMs / Merged Product	Elevation	? / Varies (See Reference)	50mpp	82S - 90S	Current	GeoTIff	?	University College London	PSA Guest Facility	Putri et al. (2019)
499	Mars	High Resolution Stereo Camera Derived DEMs (> 1250)	Elevation	<100m / <4m	up to 50mpp	Regional	Current	IMG, GeoTiff	?	HRCS Team / DLR	PDS, PSA	Gwinner et al. (2010); Dumke et al. (2010)
499	Mars	HRSC South Pole Orthoimages / Orthomosaic	Elevation	? / Varies (See Reference)	12.5mpp	82S-90S	Current	GeoTiff	?	University College London	PSA Guest Facility	Putri et al. (2019)
499	Mars	CaSSIS DEM	Elevation	? / ?	∼20mpp	Regional	Current	GeoTiff, JPEG2000	?	CaSSIS Team	CaSSIS Team	Conway et al. (2018); Re et al. (2019)
499	Mars	ASU HiRISE Dervied DEM (>600)	Elevation	Varies / <1m	1-2mpp	Regional	Current	IMG	?	UA / USGS	PDS	Kirk et al. (2008); University of Arizona (2019)
499	Mars	CTX Derived DEM	Elevation	?/?	20mpp	Regional	Current	IMG, Cube, GeoTiff	?	USGS	PDS Annex	Fergason et al. (2018); Fergason et al. (2017)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
499	Mars	USGS Derived Landing Site CTX Orthomosaics	Absolutely Controlled Orthoimages	?/?	5mpp	Regional	Current	IMG, Cube, GeoTiff	?	USGS	PDS Annex	Fergason et al. (2018); Fergason et al. (2017)
499	Mars	USGS Derived Human Exploration CTX Orthomosaics	Relatively Controlled Orthoimages	100m / ?	5mpp	Regional	Current	IMG, Cube, GeoTiff	?	USGS	PDS Annex	Hare et al. (n.d.)
499	Mars	HiRISE Orthomosaics	Absolutely Controlled Orthoimages	Varies / <1m	0.25mpp	Regional	Current	IMG, JPEG2000	?	UA, USGS	PDS	Kirk et al. (2008); University of Arizona (2019)
499	Mars	High Resolution Stereo Camera Derived Orthoimages (>1250)	Absolutely Controlled Orthoimages	<100m/ <4m	up to 12.5mpp	Regional	Current	IMG, JPEG2000	?	HRSC Team, DLR	PDS, PSA	Gwinner et al. (2010)
499	Mars	University College London Co-Registered Hi-resolution Data	Relatively Controlled Orthoimages	?/?	Varies	Regional	Current	?	iMars (?)	University College London	?	Sidiropoulos and Muller (2016); Sidiropoulos and Muller (2016)
499	Mars	Murray Lab Global CTX	Semi-controlled Unrectified Image Mosaic	?/?	5mpp	88S-88N	Current	GeoTiff	WMS	California Institute of Technology	California Institute of Technology	Dickson et al. (2018)
499	Mars	Mars Digital Image Mosaic 2.1 (Control Network)	Geodetic Coordinate Reference Frame (or Proxy)	Average: 200m Max: 1000m/10m	N/A	Global	Current	Cube Control Network, PVL	?	USGS	USGS	Archinal et al. (2003)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
499	Mars	Mars Digital Image Mosaic 2.1	Absolutely Controlled Orthomosaics	Average: 200m Max: 1000m/ 10m	231mpp / 256ppd	Global	Current	IMG, Cube, GeoTiff	WMS	USGS	PDS Annex	Kirk et al. (2001); Archinal et al. (2003)
499	Mars	THEMIS Day IR Orthomosaic	Absolutely Controlled Orthomosaics	150m - 275m / ?	100mpp	60S - 60N	Current	IMG, Cube, GeoTiff	WMS	USGS	PDS Annex	Fergason et al. (2013)
499	Mars	THEMIS Night IR Orthomosaic	Absolutely Controlled Orthomosaics	150m - 275m / ?	100mpp	60S - 60N	Current	IMG, Cube, GeoTiff	WMS	USGS	PDS Annex	Fergason et al. (2013)

Table 5: Foundational data products for Mars (21) and it's two satellites, Phobos (7) and Deimos (2). We have combined the many foundational regional elevation and orthoimage products into a single entry.

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
501	Io	Galilelo SSI / Voyager Global Mosaic	Absolutely Controlled Unrectified Mosaic	1km/?	1 - 10kmpp	85N - 85S	Current	GeoTiff	WMS	USGS	USGS	T. Becker and Geissler (2005); Archinal et al. (2001)
501	Io	Rand Control Network	Geodetic Coordinate Reference Frame (or Proxy)	N/A	N/A	Global	Unreleased	?	?	RAND / USGS	Unreleased	M. Davies et al. (1979)
501	Io	Stereo-dervied DEM	Elevation	<0.5 - >4km/0.2 - >1.6km	1kmpp (equator)	75%	Current	Cube	?	White et al.	AGU	White et al. (2014)
502	Europa	Rand Control Network	Geodetic Coordinate Reference Frame (or Proxy)	N/A	N/A	Global	Unreleased	?	Flat files	RAND	USGS	M. Davies et al. (1979)
502	Europa	Controlled Photomosaic Map of Europa, Je 15M CMN	Relatively Controlled Image Mosaic	?/?	200m - 20kmpp	Global	Current	GeoTiff	WMS	USGS	USGS	U.S. Geological Survey (2002)
502	Europa	Europa Supermosaic	Uncontrolled Image Mosaic	?/?	?	Global(?)	Unreleased	?	?	G. Collins	Unreleased	?
503	Ganymede	RAND Control Network	Geodetic Coordinate Reference Frame (or Proxy)	N/A	N/A	Global	Current	?	?	Rand	Unreleased	M. Davies et al. (1979)
503	Ganymede	Galileo/Voyager Global Mosaic	Uncontrolled Image Mosaic	?/?	400m - 20kmpp	Global	Current	GeoTiff	WMS	USGS	USGS	?
504	Callisto	Rand Control Network	Geodetic Coordinate Reference Frame (or Proxy)	N/A	N/A	Global	Unreleased	?	?	Rand	?	M. Davies et al. (1979)
504	Callisto	Galileo/Voyager Global Mosaic	Uncontrolled Image Mosaic	?/?	400mpp - 60kmpp	Global	Current	GeoTiff	WMS	USGS	USGS	U.S. Geological Survey (2001)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
599	Jupiter	Gravity Model	Gravity	?/?	?	Global	Unreleased	?	?	Iess, et al.	Unreleased	Iess et al. (2018); Buccino et al. (2018)

Table 6: Discovered foundational and non-foundational data products for Io, Europa, Ganymede, Callisto, and Jupiter

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
601	Mimas	Shape Model	Elevation	?/?	?	Global	Current	ICQ, Tab	?	Gaskell	PDS	R. W. Gaskell (2013b)
601	Mimas	Cassini Stereo Derived Topography	Elevation	?/?	?	Semi-Global	Unreleased	?	?	Shenk	Unreleased	P. Schenk (2010)
601	Mimas	Cassini ISS Global Mosaic	Semi-controlled Unrectified Image Mosaic	?/?	700mpp to ¡ 200mpp	Semi-Global	Current	IMG, PDF, PNG	WMS	DLR	DLR, PDS	Roatsch et al. (2018)
602	Enceladus	Shape Model	Elevation	?/?	?	Global	Unreleased	?	?	USGS	Unreleased	M. T. Bland et al. (2019); M. Bland et al. (2019)
602	Enceladus	Cassini Stereo Derived Topography	Elevation	?/?	?	Semi-Global	Unreleased	?	?	Shenk	Unreleased	P. Schenk (2010)
602	Enceladus	Cassini ISS Global Mosaic	Relatively Controlled Unrectified Image Mosaic	?/?	100mpp	Global	Current	GeoTiff, IMG	WMS	DLR	PDS, USGS	Roatsch et al. (2018)
603	Tethys	Shape Model	Elevation	?/?	?	Global	Current	ICQ, Tab	?	Gaskell	PDS	R. W. Gaskell (2013d)
603	Tethys	Cassini Stereo Derived Topography	Elevation	?/?	?	Semi-Global	Unreleased	?	?	Shenk	Unreleased	P. Schenk (2010)
603	Tethys	Cassini ISS Global Mosaic	Semi-controlled Unrectified Image Mosaic	?/?	32ppd / 293mpp	Global	Current	GeoTiff, IMG, PDF, PNG	WMS	DLR	DLR, PDS, USGS	Roatsch, Kersten, Matz, Scholten, et al. (2016); T. Roatsch et al. (2008)
604	Dione	Shape Model	Elevation	?/?	?	Global	Current	ICQ, Tab	?	Gaskell	PDS	R. W. Gaskell (2013a)
604	Dione	Cassini Stereo Derived Topography	Elevation	?/?	?	Semi-Global	Unreleased	?	?	Shenk	Unreleased	P. Schenk (2010)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
604	Dione	Cassini ISS Global Mosaic	Semi-controlled Unrectified Image Mosaic	?/?	154mpp	Global	Current	GeoTiff, IMG, PDF, PNG	WMS	DLR	DLR, PDS, USGS	Roatsch, Kersten, Matz, Scholten, et al. (2016); T. Roatsch et al. (2008)
605	Rhea	Cassini Stereo Derived Topography	Elevation	?/?	?	Semi-Global	Unreleased	?	?	Shenk	Unreleased	P. Schenk (2010)
605	Rhea	Cassini ISS Global Mosaic	Semi-controlled Unrectified Image Mosaic	?/?	417mpp	Global	Current	GeoTiff, IMG, PDF, PNG	?	DLR	DLR, PDS, USGS	Roatsch, Kersten, Matz, Scholten, et al. (2016); T. Roatsch et al. (2008)
606	Titan	Cassini ISS Global Mosaic	Uncontrolled Image Mosaic	?/?	11ppd / 4kmpp	95-97%	Current	GeoTiff	?	Perry et al.	USGS	Perry et al. (2005)
606	Titan	Cassini ISS Mosaic	Absolutely Controlled Image Mosaic	?/?	100ppd / 450mpp	-65 to 45	Current	GeoTiff, PNG	WMS	USGS	USGS	Archinal et al. (2013)
606	Titan	Cassini SAR Spline Interpolated Global Topography	Elevation	?/?	1ppd / 45kmpp	Global	Current	Tiff	?	Lorenz, et al.	UA, Icarus	Lorenz et al. (2013)
606	Titan	Radar Stereo-photogrammetric DEMs	Elevation	? / 200m	Varies	Regional	Current	Unreleased	?	Kirk, et al.	?	Kirk et al. (2012)
606	Titan	Altimeter Echo DEMs	Elevation	? / 35m	?	Regional	Current	Unreleased	?	Zebker, et al.	?	Zebker et al. (2009)
606	Titan	SAR Topo DEM	Elevation	? / 160m	10kmpp	5.2%	Current	Unreleased	?	Stiles, et al.	?	Stiles et al. (2009)
606	Titan	Merged / Interpolated Global DEM	Elevation	? / ?	4ppd	Global	Current	Text	?	Corlies, et al.	?	(Corlies et al., 2017)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
606	Titan	Cassini VIMS Global Mosaic	Uncontrolled mosaic	?/?	32ppd / 1.4kmpp	Global	Unreleased	?	?	Le Moulic et al.	Unreleased	Moulic et al. (2019)
608	Iapetus	Cassini Stereo Derived Topography	Elevation	?/?	?	Semi-Global	Unreleased	?	?	Shenk	Unreleased	P. Schenk (2010)
608	Iapetus	Cassini ISS Global Mosaic	Semi-controlled Unrectified Image Mosaic	?/?	16ppd / 803mpp	Semi-Global	Current	GeoTiff, IMG, PDF, PNG	WMS	DLR	DLR, PDS, USGS	Roatsch, Kersten, Matz, Scholten, et al. (2016); T. Roatsch et al. (2008)
609	Phoebe	Shape Model	Elevation	?/?	?	Global	Current	ICQ, Tab	?	Gaskell	PDS	R. W. Gaskell (2013c)
609	Phoebe	Cassini ISS Global Mosaic	Semi-controlled Unrectified Image Mosaic	?/?	233mpp	Semi-Global	Current	IMG, PDF, PNG	?	DLR	DLR, PDS	Roatsch, Kersten, Matz, Scholten, et al. (2016); T. Roatsch et al. (2008)

Table 7: Foundational and non-foundational Saturnian data products for Mimas (3), Enceladus (3), Tethys (3), Dione (3), Rhea (2), Titan (8), Iapetus (2), and Phoebe (2).

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
701	Ariel	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	25% - 45%	Current	ASCII	?	RAND.	USGS	M. E. Davies et al. (1987)
701	Ariel	Airbrush Mosaic	Controlled Unrectified Mosaic	?	?	25% - 45%	Current	PDF	?	USGS	USGS	(U.S. Geological Survey, 1988)
701	Ariel	Controlled Unrectified Images	Controlled Unrectified Images	?	?	25% - 45%	Current	IMQ	?	USGS	USGS	M. E. Davies et al. (1987)
701	Ariel	Stereoscopically Derived Topography	Elevation	?	?	25% - 45%	Unreleased	?	?	Schenk et al.	Unreleased	P. M. Schenk (2008)
702	Umbriel	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	25% - 45%	Current	ASCII	?	RAND.	USGS	M. E. Davies et al. (1987)
702	Umbriel	Airbrush Mosaic	Controlled Unrectified Mosaic	?	?	25% - 45%	Current	PDF	?	USGS	USGS	(U.S. Geological Survey, 1988)
702	Umbriel	Controlled Unrectified Images	Controlled Unrectified Images	?	?	25% - 45%	Current	IMQ	?	USGS	USGS	M. E. Davies et al. (1987)
703	Titania	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	25% - 45%	Current	ASCII	?	RAND.	USGS	M. E. Davies et al. (1987)
703	Titania	Airbrush Mosaic	Controlled Unrectified Mosaic	?	?	25% - 45%	Current	PDF	?	USGS	USGS	(U.S. Geological Survey, 1988)
703	Titania	Controlled Unrectified Images	Controlled Unrectified Images	?	?	25% - 45%	Current	IMQ	?	USGS	USGS	M. E. Davies et al. (1987)
703	Titania	Stereoscopically Derived Topography	Elevation	?	?	25% - 45%	Unreleased	?	?	Schenk et al.	Unreleased	P. M. Schenk (2008)
704	Oberon	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	25% - 45%	Current	ASCII	?	RAND.	USGS	M. E. Davies et al. (1987)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
704	Oberon	Airbrush Mosaic	Controlled Unrectified Mosaic	?	?	25% - 45%	Current	PDF	?	USGS	USGS	(U.S. Geological Survey, 1988)
704	Oberon	Controlled Unrectified Images	Controlled Unrectified Images	?	?	25% - 45%	Current	IMQ	?	USGS	USGS	M. E. Davies et al. (1987)
705	Miranda	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	25% - 45%	Current	ASCII	?	RAND.	USGS	M. E. Davies et al. (1987)
705	Miranda	Airbrush Mosaic	Controlled Unrectified Mosaic	?	?	25% - 45%	Current	PDF	?	USGS	USGS	U.S. Geological Survey (1988)
705	Miranda	Controlled Unrectified Images	Controlled Unrectified Images	?	?	25% - 45%	Current	IMQ	?	USGS	USGS	M. E. Davies et al. (1987)
705	Miranda	Stereoscopically Derived Topography	Elevation	?	?	25% - 45%	Unreleased	?	?	Schenk et al.	Unreleased	P. M. Schenk (2008)

Table 8: Uranian foundational data products. We have not identified any accuracy reporting for any of the identified products. This is entirely understandable given the limited scope and inadequate repeat coverage for robust error assessment.

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
801	Triton	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	?	Current	IMQ		USGS	USGS	M. E. Davies et al. (1991)
801	Triton	Control Network	Controlled Unrectified Mosaic	?	39ppd / 600mpp	Hemisphere	Current	GeoTiff		USGS	USGS	M. E. Davies et al. (1991)
801	Triton	Stereo-scopically Derived Topography	Elevation	?	?	25% - 45%	Unreleased	?	?	Schenk et al.	Unreleased	P. M. Schenk (2008)

Table 10. All foundational data products for the Neptunian system cover Triton.

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
901	Charon	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	?	Unreleased	ISIS	?	Shenk, et al.	Unreleased	P. M. Schenk et al. (2018b)
901	Charon	DEM	Elevation	? / 1000m - 100m	35.25ppd / 300mpp	~40% (to available data)	Current	GeoTiff, Cube	WMS	Shenk, et al.	USGS	P. M. Schenk et al. (2018b)
901	Charon	Mosaic	Absolutely Controlled Unrectified Image Mosaic	?	35.25ppd / 300mpp 35km - 0.15kmpp (actual resolution)	~40% (to available data)	Current	GeoTiff, Cube	WMS	Shenk, et al.	USGS	P. M. Schenk et al. (2018b)
999	Pluto	Control Network	Geodetic Coordinate Reference Frame (or Proxy)	?	N/A	?	Unreleased	ISIS	?	Shenk, et al.	Unreleased	P. M. Schenk et al. (2018a)
999	Pluto	Global Mosaic	Absolutely Controlled Unrectified Image Mosaic	?	69.13ppd / 300mpp	~42% (to available data)	Current	GeoTiff, Cube	WMS	Shenk, et al.	USGS	P. M. Schenk et al. (2018a)
999	Pluto	DEM	Elevation	? / 800m - 100m	69.13ppd / 300mpp	~42% (to available data)	Current	GeoTiff, Cube	WMS	Shenk, et al.	USGS	P. M. Schenk et al. (2018a)

Table 12. Identified foundational data products for Pluto (3) and Charon (3) collected by the New Horizons mission.

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
2000001	Ceres	Gravity Model	Gravity	?/?	300kmpp	Global	Current	IMG, Tab	?	Konopliv, et al.	PDS	A. S. Konopliv et al. (2012); Konopliv et al. (2018); Park et al. (2018)
2000001	Ceres	Dawn FC global DEM (HAMO)	Elevation	?/10m	60ppd / 136mpp	Global	Current	GeoTiff, IMG	?	DLR	PDS	Preusker et al. (2016); E. Roatsch T. et al. (2018)
2000001	Ceres	Dawn FC Regional DEM (LAMO)	Elevation	?/∼1.5m	256ppd / 32mpp	Regional	Superseded	IMG	?	DLR	PDS	Preusker et al. (2016)
2000001	Ceres	Regional DEMs and Mosaics	Elevation	?/∼1.5m	256ppd / 32mpp	Regional	Current	IMG	?	DLR	PDS	Jaumann et al. (2017)
2000001	Ceres	Dawn Stereo-photoclinometric (SPC) - LAMO	Elevation	?/mean 10m, 89% < 20m	100mpp	Global	Current	DSK, ICQ, IMG	WMS	Park, et al.	NAIF, PDS	Park et al. (2019); Park and Buccino (2018)
2000001	Ceres	Dawn FC global mosaic (HAMO)	Absolutely Controlled Orthomosaic	∼16m / ∼16m	140mpp	Global	Current	GeoTiff, IMG	WMS	DLR	PDS, USGS	Roatsch, Kersten, Matz, Preusker, et al. (2016)
2000001	Ceres	Dawn FC global mosaic (LAMO)	Absolutely Controlled Orthomosaic	∼16m / ∼16m	140mpp	Global	Current	GeoTiff, IMG	?	DLR	PDS, USGS	Roatsch, Kersten, Matz, Preusker, et al. (2016)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
2000004	Vesta	Gravity Model	Gravity	?/?	90kmpp	Global	Current	IMG, Tab	?	Konopliv, et al.	PDS	A. Konopliv et al. (2014, 2017)
2000004	Vesta	Dawn Stereo-photogrammetric (SPG) - HAMO	Elevation	∼8m / ∼8m	64ppd / 70mpp	∼95%	Current	GeoTiff, IMG	?	DLR	PDS	Preusker et al. (2012, 2012); Jaumann et al. (2012)
2000004	Vesta	Dawn Stereo-photoclinometric (SPC) - LAMO	Elevation	?/?	64ppd / 70mpp	Near Global	Unreleased		?	Gaskell, et al.	Unreleased	R. W. Gaskell (2012)
2000004	Vesta	Dawn FC global Mosaic (LAMO)	Absolutely Controlled Orthomosaic	?/?	20mpp	∼84%	Current	GeoTiff, IMG	?	DLR	PDS	Roatsch et al. (2013)
2000004	Vesta	Dawn FC global Mosaic (HAMO)	Absolutely Controlled Orthomosaic	∼8m / ∼8m	60mpp	Global	Superseded	GeoTiff, IMG	WMS	DLR	PDS	Le Corre et al. (2017)
2000021	Lutetia	Shape Model	Elevation	?/?	1,500,000 facets	Global	Current	VRML	?	Jorda, et al.	PDS	(Sierks et al., 2011)
2000433	Eros	Stereo-photoclinometric (SPC) Shape Model	Elevation	?/?	$(512 + 1)^2$ Vertices / Face	Global	Current	Tab, ICQ	?	Gaskell, et al.	PDS	R. W. Gaskell (2008)
2002867	Steins	OSIRIS Derived SPC Derived Shape Model	Elevation	20m / ?	> 70m / facet	Global	Current	VRML	?	Jorda, et al.	PDS	(Jorda et al., 2012)
2025143	Itokawa	Stereo-photoclinometric (SPC) Shape Model	Elevation	?/?	$(256 + 1)^2$ Vertices / Face	Global	Current	Tab, ICQ	?	Gaskell, et al.	PDS	R. Gaskell et al. (2006)
2101955	Bennu	Shape Model	Elevation	10m / 52m	25m between vertices	Global	Current	Tab, Obj, Wavefront	?	Nolan, et al.	PDS	Nolan et al. (2013)
2162173	Ryugu	Structure From Motion (SfM) Shape Model	Elevation	?/?	?	Global	Unreleased	?	?	University of Aizu	Unreleased	JAXA (n.d.)

ID	Body	Product Name	Product Type	Horizontal / Vertical Accuracy	Resolution	Coverage	Status	Offline Formats	Online Formats	Source (Producer)	Data Providers	References
2162173	Ryugu	Stereo-photoclinometric (SPC)) Shape Model	Elevation	?/?	?	Global	Unreleased	?	?	Kobe University, University of Aizu	Unreleased	JAXA (n.d.)
1000005	Borrelly	Stereo-photogrammetric Shape Model	Elevation	? / 100m	500m	∼50%	Current	TAB	?	Oberst, et al.	PDS	Oberst et al. (2004)
1000005	Borrelly	Stereo-photogrammetric Shape Model	Elevation	? / 100m	500m	∼50%	Current	TAB	?	USGS	PDS	Kirk et al. (2004)
1000012	Comet 67P/C-G	NavCam Derived SPC Shape Model	Elevation	?/?	>4,000,000 facets	Global	Current	DSK, ROS	?	ESA, Rosetta Mission	PDS	ESA (2017)
1000012	Comet 67P/C-G	OSIRIS SPC Derived Shape Model	Elevation	<2m / <2m	>5,000,000 plates, 1-2m maplets	Global	Current	DSK, VRML	?	Gaskell, et al.	PDS	Preusker et al. (2015)
1000012	Comet 67P/C-G	OSIRIS Derived SPG Model	Elevation	<2m / <2m	2m, >16,000,000 facets	Global	Current	DSK, VRML	?	DLR	PDS	Preusker et al. (2015)
1000012	Comet 67P/C-G	Multiresolution Photoclinometry by Deformation Shape Model	Elevation	?/?	>1,000,000 plates	Global	Current	DSK, VRML	?	Jorda, et al.	PDS	Jorda et al. (2016); Capanna et al. (2015)
1000041	Comet 103P / Hartley 2	EPOXI Derived Shape Model	Elevation	10m (visible) 30m (silhouettes) / 18m	> 32,000 plates	Global	Current	TAB, VRML	?	Thomas, et al.	PDS	P. Thomas et al. (2013)
1000093	Comet Tempel 1	Deep Impact Derived Shape Model	Elevation	20m/20m	> 32,000 plates	Global	Current	TAB	?	Thomas, et al.	PDS	P. C. Thomas et al. (2007)

Table 13: Identified foundational data products for small bodies not associated with a particular primary body. Asteroids that have been the targets of satellite mapping operations are identified by NAIF codes in the 2000000 range. Likewise, comets that have been the target of mapping operations are identified by NAIF codes in the 1000001 range. For the ESA generated SPC shape model of Comet 67P/C-G the '.ros' format is a custom format adopted by the Rosetta mission team.

4 Conclusion

Prior to making widespread use of foundational data products to drive the generation, co-registration, and use of framework data products it is necessary to survey the current state of knowledge. In this work, we have provided a more stringent definition of what constitutes a foundational data product. Specifically, we have tightened our previous definition for image data to assert that, at the purest form, only absolutely controlled and properly orthorectififed image products are foundational. In the absence of the necessary geodetic coordinate reference frame definitions and elevation data sets, absolutely controlled non-orthorectififed image products, relatively controlled image products, and semi-controlled image products can serve as interim foundational data products.

We have identified well over 100 foundational data products, reported on internal data quality, interoperability, and provided a reference, where available. In general, the planetary science community has a wide array of products available to support geospatial studies. We note a general lack of calibrated and orthorectified (to the best available shape) image data at the per-image scale. Therefore, the individual research scientist can gain access to large-extent orthomosaics, but must process individual images. This processing step has a non-trivial cost that is spread across the entire planetary science community (e.g. Malik & Foster, 2012).

The identification of these products supports three goals. First, each body should have at least four entries describing a gravity model, a geodetic coordinate reference frame or proxy, an elevation data set, and orthomosaic data. The lack of a particular entry for an object represents the opportunity to create, assess, and publish a foundational data product. Second, foundational data products must be well described in peer-reviewed publications and made freely available to users. In instances where this is not the case, we hope that merely identifying that further work is possible will empower improved transparency. Finally, product identification is the first step necessary to realize a data clearing house and a Planetary Spatial Data Infrastructure (Laura et al., 2017).

This process of data discovery to identify available foundational data products highlighted the challenges researchers face discovering suitable data. In the best case, we were aware of a product through experience using, developing, or archiving it. With a product name, it was usually possible to rapidly discover a conference abstract, peer-reviewed publication, or data repository. Naturally, the discovery process for data sets that we did not know about was significantly more challenging due to the lack of any type of geoportal or data portal (Beyer et al., 2018). Most challenging, were those works where the data were delivered to the PDS and we were unable to identify any associated peer-reviewed or conference publication, and those instances where publications were generated, but the data were never made available.

Once discovered, we also note that many publications did not explicitly describe spatial accuracy, the reference frame to which the product was tied, or the potential interoperability between data sets. This is not surprising given both the wealth of topical science that is possible with a single data set and the relatively recent efforts to bring this type of metadata to increased prominence. We hope that the community can identify standards and policies to support increased data product metadata reporting.

Finally, in evaluating the entire set of foundational data products, it is clear that more recent flight missions have placed increased importance on the creation, assessment, and publication of foundational data products. We hope that this trend continues and that data from previous missions can be reassessed and integrated into the corpus of spatially enabled data products in order to support the widest possible array of planetary science research.

5 Acronyms

Ames NASA Ames Research Center
AGU American Geophysical Union
APL John Hopkins University Applied Physics Laboratory
ASU Arizona State University
ACTC Applied Coherent Technology Corporation
CNSA Chinese National Space Administration
CaSSIS Colour and Stereo Surface Imaging System
CTX Context Camera
Cube The ISIS Cube Format
DARTS Data ARchive and Transmission System
DAT A plain text archival format
DEM Digital Elevation Model
DLR Deutsches Zentrum für Luft- und Raumfahrt
DN Digital Number
ESA European Space Agency
GIS Geographic Information System
GMM-3 Goddard Mars Model 3
GMM-2B Goddard Mars Model 2B
GRAIL Gravity Recovery and Interior Laboratory
GRAS Data Release and Information Service System of China's Lunar Exploration Program
GSFC Goddard Space Flight Center
HAMO High Altitude Mapping Orbit
HiRISE High Resolution Imaging Science Experiment
HRSC High Resolution Stereo Camera
IAU International Astronomical Union
ICQ Implicitly Connected Quadrilateral Format
IMG PDS3 Compliant Image Storage Format
IMQ A PDS3 compliant compressed data format
ISRO Indian Space Research Organization
ISDA Indain Science Data Archive
IR Infrared
JAXA Japan Aerospace Exploration Agency
kmpp kilometers per pixel
JPL Jet Propulsion Laboratory
LAMO Low Altitude Mapping Orbit
LALT Kaguya/Selene Laser Altimeter
LOLA Lunar Orbiter Laser Altimeter
LROC Lunar Reconnaissance Orbiter Camera
MC Mars Quadrangle
MEGDR Mission Experiment Gridded Data Record
MESSENGER Mercury Surface Space Environment, GEochemistry, and Ranging
MEX Mars EXpress
MGS Mars Global Surveyor
MIDR Mosaicked Image Data Record
MLA Mercury Laser Altimeter
MOC Mars Orbiter Camera
MOLA Mars Orbiter Laser Altimeter
mpp meters per pixel
MRO Mars Reconnaissance Orbiter

NAC Narrow Angle Camera
NASA National Aeronautics and Space Administration
NEO Near Earth Object
NIR Near Infrared
OGC Open Geospatial Consortium
OSU Ohio State University
PDS Planetary Data System
ppd pixels per degree
PSA Planetary Science Archive
PSDI Planetary Spatial Data Infrastructure
SAR Synthetic Aperture Radar
SBMT Small Bodies Mapping Tool
SDI Spatial Data Infrastructure
SfM Structure from Motion
SPC stereophotoclinometric
SSI Solid State Imager
TC Terrain Camera
THEMIS THErmal EMission Imaging System
TMC Terrain Mapping Camera
UA University of Arizona
USGS United States Geological Survey
VIS Visible Spectrum
VRML The PDS Small Bodies Node Archival Shape Model Format
WAC Wide Angle Camera
WMS Web Mapping Standard

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