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Product Description for “Rhea SPC Shape Model and Assessment Products”
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This package contains global topography and albedo data generated by the Gaskell Stereophotoclinometry (SPC) software suite for the Saturnian satellite Rhea. This global Rhea model is the first archived within the PDS. It includes 2719 images, which are all the available images with the last image taken 15 Feb 2015. The images used to generate the model are Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) calibrated Cassini 32-bit images from the Ring-Moon Systems Node of NASA’s Planetary Data System (PDS) (see Acknowledgments section). The image calibration corrects for camera effects including dust rings, which cause minor topography errors in rare situations. A geometric distortion correction is applied to all images. The kernels are from the Navigation and Ancillary Information Facility (NAIF), though a few kernels were “flight kernels” that are no longer available to the public, but should be similar to those archived at NAIF. Images and kernels were added to the model in various stages over the past decade as data came in and the model was improved. The kernels are only used to determine the initial position and pointing of the spacecraft. Afterwards, the position and pointing are updated by SPC as the model improves, so the kernels used are not primary inputs. Images and kernels used to build the global model can be found in document/rheaimagelist.txt and document/rheakernellist.txt. To aid data users in the quality of the global topography, the rheashapeassessment.pdf in the document directory contains plots of the assessment data of the global DTM.

Global Model:

Object Name	ICQ Spacing for Q=512 / Q=128	IAU Mean Radius*
Rhea	2.15 / 8.6 km GSD	763.5 km
* From Archinal et al. (2018)		

The native SPC format for a global model is the implicitly connected quadrilateral (ICQ). Each of the quadrilaterals in a model will have the same size, and we refer to this size as “Q”. Larger values of Q will thus give a higher resolution model. The equation to determine the number of vertices from the Q size is $6*(Q+1)^2$ (Gaskell, 2020). We provide the ICQ model with a Q of 512 (1,579,014 vertices), and 128 (99,846 vertices). For each model, the distance between vertices is approximately the same over the whole model, and we refer to this distance as the Ground Sample Distance (GSD). We also provide the global model in other formats, which are discussed below.

Thomas (2010) determined the a, b, and c axes for Rhea. A triaxial ellipsoid generated from the Thomas values match the limbs of Cassini images well, though this SPC model provides a better fit. Nonetheless, there is compatibility between this work and Thomas (2010). A comparison of these two models with an example Cassini image is given in document/rheavisualcmp.pdf. Note that this type of model to image comparison is routinely performed during SPC processing, and is one of the ways the SPC model is validated.

Topography and Albedo Data

The global topography and albedo data is provided in various formats. For the global topography model the formats include the native SPC format of Implicitly Connected Quadrilateral (ICQ), in addition to plate vector (PLT) and Object Vector (OBJ) formats readable by programs like the Small Body Mapping Tool (SBMT), cubes (.cub) readable by the USGS ISIS program, and geoTiff which can be read by GIS programs such as ArcGIS. The global albedo data is provided in cube and geoTiff formats. Note that the topography is the primary product of SPC, while the albedo is a secondary product. The albedo accuracy has not been investigated as thoroughly as the topographic accuracy.

Topographic Accuracy of SPC DTMs:

The topographic error of SPC DTMs was estimated as a part of the OSIRIS-REx mission. As part of NASA Class B software validation, Weirich et al. (2022) used a synthetic, but realistic, digital asteroid model with known heights to produce a simulated mission image suite. Note that this test was performed with an early version of the mission image suite, which had less stereo than the flown mission. With only these images, and no access to the synthetic asteroid, we generated an SPC global DTM. This global SPC DTM was then compared to the original synthetic DTM to characterize the actual errors. Weirich et al. (2022) showed that a sufficient, but not ideal, image set produced DTMs that were typically accurate to one image pixel of the finest-resolution image. The global imagining campaign for Rhea is considered sufficient (even approaching ideal at some locations near the equator), so the one image pixel accuracy stated in the previous sentences applies to the products in this bundle. See Weirich et al. (2022) for definitions of a sufficient and ideal image set. Also see Palmer et al. (2022, 2024) and Barnouin et al. (2020) for descriptions of good and poor imagery for SPC. The worst vertex in the test DTM was accurate to about three image pixels of the finest-resolution image. Note that these errors are for both the vertical (i.e. radial) and horizontal directions.

Unlike the OSIRIS-REx testing, we did not build the Rhea DTMs with a GSD of the finest-resolution image, therefore the accuracy is estimated to be one DTM GSD. Likewise, the worst DTM vertex is estimated to be accurate to three DTM GSD. A good rule of thumb is to estimate the accuracy of the DTMs to be one to two DTM GSD. This gives 2.15 to 4.3 km for the global DTM. To better understand the accuracy of the topography data, we provide further details in the section titled “Quality Assessment Data” in this document.

SPC has a critical internal consistency check that provides an evaluation of the quality of the DTM, specifically the formal uncertainty, or FormU (Weirich et al., 2022). The FormU indicates how closely the data from the model matches the image data. While the one to two DTM GSD is the estimated accuracy of an individual vertex determined from a test case (i.e. OSIRIS-REx pre-launch testing), FormU is instead a holistic value for a specific DTM. The FormU for the maplets with the best global coverage, that of the 1000 m maplets, is 286.4 m. Although FormU is a measure of internal consistency, and not accuracy, Weirich et al. (2022) found the FormU to be within a factor of 2 of the actual error for the OSIRIS-REx testing models. Since the best maplets and the FormU are better than the GSD of the global DTM, we have a good indicator that the error is likely 1 to 2 GSD, confirming the numbers in the previous paragraph.

Formats:

ICQ: The native SPC format for a global model is the implicitly connected quadrilateral (ICQ), and the ICQ models in this bundle have a Q of 512 or 128. The file format is ASCII text with three columns (if topography only) or four columns (if topography and albedo). The ICQ files in this bundle are all four columns. The first three columns are the X (column 1), Y (column 2), and Z (column 3) of the radius vector with units of kilometers, set in the body fixed frame. The +X axis defines 0 degrees longitude, while the +Z axis defines the positive pole (i.e. North Pole for prograde rotation). The fourth column is relative albedo, though we nonetheless still refer to it simply as "albedo". The albedo is a number that varies between 0 (darkest) and 2 (brightest) with the average being 1. Photometric modeling is needed to convert these "albedo" values to an albedo with physical meaning, such as geometric albedo. Further details of the ICQ format and SPC in general, as well as Fortran code to read in the ICQ format, can be found in Gaskell et al. (2008) and Gaskell (2020), respectively. All values are valid, but we still assign a “missing constant” value to the xml label.

All ICQ files end with an "i" to distinguish them from other files.

PLT and OBJ: As previously stated, PLT is a plate model, while OBJ is an object vector readable by the SBMT. These files were generated using the Applied Physics Lab Altimetry Working Group tools generated for the OSIRIS-REx mission. The programs used are ICQ2PLT and PLT2OBJ (see Acknowledgments section). The OBJ files generated by PLT2OBJ have been modified to reduce the number of significant figures and the columns have been padded with white spaces to align all columns. Both formats are in units of kilometers. All values are valid, but we still assign a “missing constant” value to the xml label.

All PLT files end with a "p" to distinguish them from other files.

All OBJ files end with a "o" to distinguish them from other files.

Cubes: The topography and albedo of the Q=512 model are provided as separate cubes, both with global equirectangular projection and square pixels. They are resampled values from the ICQ generated by SPC. The SPC data was converted to a cube using the Generic Mapping Tool (GMT) programs blockmean and sphinterpolate, followed by the Geospatial Data Abstraction Library (GDAL) program gdal_translate. The cube geometry block was then set using ISIS maptemplate and maplab. The topography is given as radius in meters. The horizontal spacing is kept close to that of the ICQ GSD. All values are valid, but we still assign a “missing constant” value to the xml label.

All Cube files end with a "c" to distinguish them from other files.

GeoTiff: The topography and albedo of the Q=512 model are provided as separate geoTiffs with global equirectangular projection and with square pixels. They were generated from the cubes using the GDAL program gdal_translate. As such, they are also resampled values from the ICQ generated by SPC, and are in units of meters. These files are 32-bit, which is required to obtain the spatial resolutions needed for some solar system bodies. To provide data product similarity across all bodies, we always generate 32-bit geoTiffs even when high spatial resolution is not needed. 32-bit geoTiff files cannot be read by simple programs and require programs such as ArcGIS to be accessed. All values are valid, but we still assign a “missing constant” value to the xml label.

All geoTiff files end with a "g" to distinguish them from other files.

Global DTM Quality Assessment Data

We provide metadata for the global DTM to understand the quality of the topography and albedo data, as well as to provide information about where future high-resolution regional DTMs could be generated and the expected quality of their data. This metadata is in the form of sigma values of the topography, best maplet resolution, number of images, and best image resolution. All quality assessment data is provided in USGS ISIS cube format. We provide images of these products, along with our assessment of each, in document/rheashapeassessment.pdf.

To better understand the sigma values and best maplet resolution, a brief description of an SPC maplet is given here. Further details can be found in Palmer et al. (2022). A maplet is a DTM that is usually 99 x 99 vertices and represents a portion of the surface. Maplets can have any vertex spacing, also called ground sample distance (GSD), and are placed to overlap with other maplets. Initial stages of the global DTM are made with large maplets, and as the global DTM develops, smaller and smaller maplets are used. The result is every portion of the surface has multiple maplets with many different GSD values.

Similar to the global radius and albedo in cube format, all assessment data uses an equirectangular projection with square pixels. All assessment products are in 1-degree bins, and have 360 by 180 pixels.

Best Maplet Resolution:

The best maplet resolution is given in units of meters in cube format. Note that the maplet resolution for SPC models can be any value, and this value can be better or worse than the GSD of the global DTM, and better or worse than the best image resolution. In the case of this Rhea model the maplet GSD is always better (i.e. smaller) than the global DTM, and usually (~85% of the surface) worse than the best image resolution. A “missing constant” value is assigned in the xml label because there are some sampling gaps near the poles.

Sigma Values:

The sigma value is a measure of how well all the maplets agree at a particular vertex on the global DTM, with smaller values indicating better agreement. Note that the sigma is not a measure of the error of the radius at that vertex, rather it is a measure of internal consistency between the model and the images. Nonetheless, the more the maplets differ in their height, the less likely the final radius will be close to the truth.

SPC returns the sigma value in meters for each vertex of the global DTM. We downsample these sigma values into 1-degree bins using GMT. All portions of the surface are valid, but we assign a “missing constant” value in the xml label.

Best Image Resolution:

Best image resolution refers to the best or finest-resolution image used at every vertex. The best image resolution is given as meters. All values are valid, but we assign a “missing constant” value in the xml label.

Number of Images:

Typically more images indicate more accurate heights. SPC has a theoretical lower limit of three images, though in practice five images are an effective lower limit due to less than optimum observation geometries. Areas with fewer than five images should be treated with caution. In this Rhea model, all areas have five or more images, indicating accurate heights. In general, the number of images is the least useful quality assessment since it does not capture the uniqueness of the viewing conditions. An example of a poor observation set is one in which there are five images taken one second apart. The sun vector has not changed and the spacecraft vector has not changed appreciably, so those five images are effectively one unique image. Another example is a single spacecraft flyby with ten images of the same region on the surface, versus ten spacecraft flybys from different angles, each with a single image of the same surface. The latter is far better than the former even though they each have ten images. The latter is better because it will have a larger variety of emission and incidence angles (see Palmer et al. 2024 and Barnouin et al. 2020 for details, and a description of good and poor imagery). Another limitation to be aware of is that low resolution images are counted even if they do not contribute to the solution. An example is five good images at 300 m/px, and fifty images at 3,000 m/px. The number of images will be 55, even though effectively there are only five images contributing to the solution.

Nonetheless, we feel it is still a good qualitative measure of quality, and can highlight low quality areas of the surface that would otherwise appear to be high quality. An example is a portion of the surface with high image resolution, but only three images.

All values are valid, but we assign a “missing constant” value in the xml label.

Formats

Cubes: All assessment data is provided in USGS ISIS cubes, as well as thumbnails in document/rheashapeassessment.pdf. As stated above, all products are given in 1-degree bins with an equirectangular projection. All cube files end with a "c" to distinguish them from other files.

File Naming Schema

All global product filenames begin with “rhea”, followed by a <type> identifier. For the table files, the <type> identifier is “128” for the Q=128 model or “512” for the Q=512 model. For the remaining global products the <type> identifier is “albedo”, “radius”, “sigma”, “bestmap” for the best maplet resolution, “bestimg” for the best image resolution, and “numimg” for the number of images. The <format> identifier is one character to make the xml labels unique. The <format> identifiers for the table files are “i”, “p”, and “o”, for ICQ, plate vector, and object vector, respectively. For remaining global products ”c" will be used for cubes, "g" will used be for geoTiff.

Global examples:
rhea_512_i.tab
rhea_bestmap_c.cub

Acknowledgments

There is currently no PDS4 bundle for the calibrated image data, but the data was generated by the Ring-Moon Systems Node and is available from the Outer Planets Unified Search (OPUS) tool found at https://pds-rings.seti.org/search/. Porco et al. (2005) is the PDS3 working citation for this data.

The programs used to generate the PLT and OBJ files were from the altimetry working group (AltWG) of the OSIRIS-REx mission. While these tools are not currently available to the public, a newer version of the programs, ShapeFormatConverter, is available on GitHub as part of the “Terrasaur” software package (https://github.com/JHUAPL/Terrasaur).

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