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Product Description for “Ceres SPC Shape Model and Regional Models of Permanently Shadowed Regions
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This package contains global and regional topography and albedo data generated by the Gaskell Stereophotoclinometry (SPC) software suite for asteroid Ceres. The regional models are the primary products of this archive, and were generated using secondary illumination (i.e. light reflected off crater walls) to obtain heights in permanently shadowed regions (PSR). The global model is provided as context for the regional models, but the global model is of high quality and can be used independently. These Digital Terrain Models (DTM) of Ceres were generated by R. Gaskell. The images used to generate the models are from the PDS Small Bodies Node, and the kernels are from the Navigation and Ancillary Information Facility (NAIF). Images and kernels used to build the global model can be found in document/ceresimglist.txt and document/cereskernellist.txt, respectively. Text files listing the images used for each regional model are also provided in the document directory. To aid data users in the quality of the global topography, the ceresglobalassessment.pdf in the document directory contains plots of the assessment data of the global DTM.

The native SPC format for a global model is the implicitly connected quadrilateral (ICQ). Larger values of Q (i.e. the number of data points on one side of a quadrilateral) will give a higher resolution model. We provide the ICQ model with a Q of 512 (1,579,014 vertices), and 128 (99,846 vertices). For each individual model (regional or global), 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.

Regional Models:

Location Name	Center Lat/East Lon deg	Size (km)	GSD (m)	Residual Error (m)*
np04n86079	86 / 079	9.9	100	195
np05n70114	70 / 114	9.9	100	56
np07n78354	78 / 354	9.9	100	350
np19n82316	82 / 316	9.9	100	81
np26n79259	79 / 259	9.9	100	71
np65n73057	73 / 057	4.0	40	90
np66n82216	82 / 216	4.0	40	67
sp01s71031	-71 / 031	9.9	100	134
sp02s70168	-70 / 168	4.0	40	85
* See section “Topography and Albedo Data” for details				

Global Model:

Object Name	ICQ Spacing for Q=512 / Q=128	Mean Radius
Ceres	1.3 / 5.3 km GSD	470 km

Our global Ceres model is the third archived within the PDS. The first global model was generated using stereo techniques by DLR (German Aerospace Center), which only used HAMO (High Altitude Mapping Orbit) images (Roatsch et al., 2016). The second model was generated using SPC by JPL (Park and Buccino, 2018), and used both HAMO and LAMO (Low Altitude Mapping Orbit) images. Although the end product of the JPL SPC model was made available to the public, the image alignment and ancillary data (i.e. an SPC data directory) was not provided. A global SPC data directory is needed to ensure regional models are all correctly oriented with respect to each other, so a new SPC data directory was generated, resulting in a third global Ceres DTM. A full evaluation of this new model compared to the previous models is outside the scope of this bundle. However, we performed a preliminary examination between our model and the Q=512 JPL model. We found them grossly similar upon visual inspection, and calculate an RMS deviation of 221 meters between the JPL model and the model provided here.Our regional models align very well with the JPL model, and closely with the DLR model. The regional models visually have finer details such as smaller craters not seen in the other models.

Topography and Albedo Data

We generated the Digital Terrain Models (DTM) using Dawn images for Ceres. The topography and albedo data are provided in various formats, depending upon whether it is global or regional data. For the global model, the topography formats include the native SPC format of Implicitly Connected Quadrilateral (ICQ), 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 (.tif) which can be read by GIS programs such as ArcGIS. The global albedo data is provided in cube and geoTiff formats. For the regional models, the formats for topography and albedo are cubes and geoTiff. Note that the topography is the primary product of SPC. The albedo is a secondary product and therefore may not be as accurate as the topography. 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 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 fewer stereo images 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 Ceres and the regional DTMs are considered sufficient, so the one image pixel accuracy stated in the previous sentences also 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) 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 Ceres 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 to estimate the accuracy of the DTMs is one to two DTM GSD. This gives 1.3 to 2.6 km for the Q=512 global DTM, 5.3 to 10.6 km for the Q=128 global DTM, 100 to 200 m for the regional models that begin with “sp01” or “np04” through “np26”, and 40 to 80 m for the remaining regional models. 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 imagery 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 is often given for only the highest-resolution maplets, but that will not be sufficient for the Ceres global model because the highest-resolution maplets have such small coverage. Instead, we give the FormU for the maplets with the best global coverage, that of the 160 m maplets. These maplets have a FormU of 57.3 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 much better than the GSD of the global DTM, we have a strong indicator that the error is likely 1 to 2 GSD, confirming the number in the previous paragraph. The regional DTMs are generated from a single maplet, so we cannot calculate a FormU for them. Instead, we calculate the residual error for each maplet, and list this value (under Residual Error) in the Table above for each location.

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 contain 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 0.5. 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, can be found in Gaskell et al. (2008). Fortran code to read in the ICQ format can be found in icqmodel.asc from Gaskell (2020). All values are valid, but we still assign a “missing constant” value to the xml labels.

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 tools generated for the OSIRIS-REx mission. The programs used are ICQ2PLT and PLT2OBJ. 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. In order for some programs to ready the OBJ file, the “.tab” extension should be renamed to “.obj.” 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 an "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.

The cubes for the regional DTMs are not projected but approximate north up, though since these locations are near the poles they can deviate up to 45 degrees from north up. Orientation vectors are given in the PDS label under local_georeference_information. The regional cubes are given in "SPC space" so that resampling of the SPC data does not occur. The horizontal spacing between the vertices is the GSD of the DTM. Three cubes fully define the topography. These are topography, latitude, and longitude cubes. The topography cube is the elevation value in meters from Ceres' datum of 470 km, the latitude cube is the Latitude value of that vertex in degrees, and the longitude cube is the East Longitude value of that vertex in degrees. A fourth cube is for the relative albedo of each vertex, so the latitude and longitude cubes apply to albedo as well as topography. Note that all values in the topography, latitude, longitude, and albedo cube files are valid, but we still assign a “missing constant” value of 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.

The geoTiffs for the regional DTMs are projected in either stereographic, north pole or south pole, depending on the latitude, and have square pixels. Like the global DTMs, they represent resampled values from the topography generated by SPC, which involves smoothing of the data. The SPC data was projected in vector space using the GDAL program ogr2ogr, then converted to a gridded geoTiff using the program gdal_grid using an Inverse Distance Weighting (IDW) algorithm. The program parameters were a search radius of the DTM’s GSD, a power value of 2, smoothing value of 1, minimum of 1 point, and a maximum of 12 points. If there were not enough valid vertices to meet these criteria, then the NoData value found in the xml label is written. Since the data is projected onto a sphere and is not in planar format, measuring planar distances will not give the correct distance. Users should be warned that many programs default to measuring planar distances. Likewise, multiplying the GSD by the number of pixels in the x- and y-direction will not give the correct distance. Instead the geodesic distance must be measured, and this is the value shown in the Table at the beginning of this document. A single topography geoTiff records the elevation in meters from Ceres's datum of 470 km, as well as the latitude and longitude of each vertex. The albedo is also provided in geoTiff format, and is generated using the same pipeline as the topography geoTiff. Like the global DTM in geoTiff format, these files are 32-bit. The “missing constant” value used for these geoTiffs can be found in 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/ ceresshapeassessment.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. If imagery allows, 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. The best maplet resolution could be the same everywhere, but for this Ceres model the maplet resolution is better at polar craters since we are interested in the PSRs. 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 Ceres model the maplet GSD is always better than the global DTM, and usually worse than the best image resolution. All values are valid, but we assign a “missing constant” value in the xml label.

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. 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. 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 four or five images are often the lower limit. Areas with fewer than five images should be treated with caution. In this Ceres 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 is 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. This is because it will have a larger variety of emission and incidence angles (see Palmer et al. 2022 and Barnouin et al. 2020 for details, and a description of good and poor imagery). Another example of the limitation of the number of images 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 surmise 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/ceresshapeassessment.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 “ceres”, 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:
ceres_512_i.tab
ceres_bestmap_c.cub

All regional DTM filenames in this bundle begin with a <location> identifier. This identifier has both region and central lat/lon DTM information. The first four characters will be of an abbreviated version of the region, the next three for the latitude, and the following three for longitude. The latitude is represented by an "n" for North and an "s" for South, followed by the numeric value of the latitude accurate to an integer number. The longitude is represented by the numeric value in East Longitude accurate to aninteger number.

Regional location example:
North Pole 04 86 Lat, 79 E Lon becomes np04n86079

The next identifier is <type>, which will be "topo" for topography, "lat" for latitude, and "lon" for longitude.

The last identifier is one character to make the cube and geoTiff xml labels unique. "c" will be used for cubes, while "g" will be for geoTiff.

Thus, all topography, latitude, and longitude cubes will have the filename structure:
<location>_<type>_c.cub

All topography geoTiffs will have the filename structure: <location>_topo_g.tif

Locations

This bundle contains nine DTMs. These locations were all chosen to investigate the PSR near the poles.Most of these crater host bright deposits and correspond to study sites investigated in Platz et al. (2017), Ermakov et al. (2017), and Schorghofer et al. (2024). Crater bottoms are generated using secondary illumination since there is no direct sunlight in these regions. Images used to construct each DTM are listed as <location>imglist.txt. The table below shows the correspondence among the nomenclature used in these studies and in this PDS archive.

approved_name	Ermakov	Platz	This_Repository
Bilwis Crater	NP4	#1	np04
unnamed	NP7	#3	np07
Damia Crater	NP19	-	np19
Enkimdu Crater	NP26	-	np26
Zatik Crater	NP5	#2	np05
unnamed	-	#4	np65
unnamed	-	#5	np66
unnamed	SP1	-	sp01
unnamed	SP2	-	sp02

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