

## High Resolution Enceladus Atlas derived from Cassini-ISS images

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### Abstract

The Cassini Imaging Science Subsystem (ISS) acquired 377 high-resolution images ( $< 1$  km/pixel) during three close flybys of Enceladus in 2005 (Porco et al., 2006). We combined these images with lower-resolution Cassini images and four others taken by Voyager cameras to produce a high-resolution global controlled mosaic of Enceladus. This global mosaic is the baseline for a high-resolution Enceladus atlas that consists of 15 tiles mapped at a scale of 1:500,000. The nomenclature used in this atlas was proposed by the Cassini imaging team and was approved by the International Astronomical Union (IAU). The whole atlas is available to the public through the Imaging Team's website [<http://ciclops.org/maps>].

**Keywords:** Cassini, Icy Satellites, Planetary Mapping, Saturnian system

### 1. Introduction

The Cassini spacecraft started its tour through the Saturnian system in July 2004. The Imaging Science Subsystem onboard the orbiter consists of a high-resolution Narrow Angle Camera (NAC) with a focal length of 2000 mm and a Wide Angle Camera (WAC) with a focal length of 200 mm (Porco et al., 2004). One of the main objectives of the Cassini mission is to investigate the icy Saturnian satellites. Enceladus, the second innermost of the medium sized satellites, was imaged by the Cassini spacecraft during three close flybys (Table I, Porco et al., 2006). The images taken during these flybys together with lower resolution frames allowed us to create a global mosaic of Enceladus with a spatial- resolution of about 110 m/pixel. Unfortunately, the Cassini ISS has not yet imaged the northern high latitude regions ( $> 67^\circ$ ) because they are shrouded in seasonal darkness and will not be illuminated by the Sun until later in the decade when the Cassini extended mission begins. Fortunately, the Voyager camera was able to take images from these regions during its flyby in the early 1980's. We thus used Voyager images to fill the North Polar gaps in the global mosaic.

Details of the image processing will be described in Section 2. Section 3 summarizes the high-level cartographic work that produced our high-resolution atlas, which consists of 15 maps of the different regions of Enceladus. Three examples of these maps are shown. A brief overview of future work is given in Section 4.

### 2. Data Processing

#### 2.1. Image processing

The image data returned from the spacecraft are distributed to the Cassini imaging team in VICAR (Video Image Communication and Retrieval) format [<http://www-mipl.jpl.nasa.gov/external/vicar.html>]. The first step of the image processing is the radiometric calibration of the images using the ISS Team's CISSCAL computer program (Porco et al., 2004). Next, the specific subset of images that will be used to construct the global basemap is selected. At the time of this writing, a total of 2353 images of Enceladus are available. This total data set contains images obtained through a variety of different ISS colour filters and at spatial resolutions ranging from 3 m/pixel up to 14 km/pixel. For our mosaic, we selected only those images taken with the filters CL1, CL2 or GRN, as these images show comparable albedo contrasts among different Enceladus terrains. 50 Cassini NAC images, one Cassini WAC image (Table II), and four Voyager high-resolution images were used to produce a 40 pixel/deg global mosaic. Figure 1 shows the location of the individual Cassini images. The resolution of the selected Cassini images varies between 0.064 and 8.8 km/pixel. The resolutions of the Voyager images C4398347, C4400044, C4400412, C4400432 are 8.8, 1.85, 1.0 and 1.0 km/pixel, respectively.

The next step of the processing chain is to map project the images to the proper scale and map format – a process that requires detailed information about the global shape of Enceladus. The inner Saturnian satellites are best described by tri-axial ellipsoids as derived from ISS images by Thomas et al. (2006). The latest radii for Enceladus are 256.6, 251.4, and 248.3 km. However, to facilitate comparison and interpretation of the maps, ellipsoids were used only for the calculation of the ray intersection points, while the map projection itself was done onto a sphere with the mean radius (252.1 km) (Thomas et al., 2006). The Cassini orbit and attitude data used for the calculation of the surface intersection points are provided as SPICE kernels [<http://naif.jpl.nasa.gov>] and were improved using a limb-fitting technique (Roatsch et al., 2006). We chose an equidistant map projection as our reference format. The coordinate system adopted by the Cassini mission for satellite mapping is the IAU “planetographic” system, consisting of planetographic latitude and positive West longitude. But because a spherical reference surface is used for map projections of the satellites, planetographic and planetocentric latitudes are numerically equal. The Hapke photometric model (Hapke, 1993) was applied to adjust the brightness of each map pixel so that it represents the reflectance that would be observed at the nadir at 30-deg phase angle. Imaging data viewed at incidence and emission angles greater than 80-deg were omitted from the map. After photometric correction, mosaicking was the final step of the image processing (Roatsch et al., 2006).

## 2.2. Least-squares adjustment of attitude data

A 3-D control net was set up to correct errors in the nominal camera pointing data. Here, we applied least-squares adjustment techniques (Giese et al., 2006). The image coordinates of 88 control points (Fig. 2) collected in 11 NAC images (Table III) were applied as observational data in the adjustment, and the ground coordinates of the control points and the camera pointing angles were treated as unknowns. The spacecraft orbit was fixed during the calculations. In result we obtained improved camera pointing angles and a 3-D control net with average  $1\sigma$  errors of 736 m, 335 m, 608 m for the x, y, z coordinates, respectively. Unfortunately, the control points are not equally distributed over Enceladus' surface due to missing stereo data around the prime meridian (Fig. 2).

The improved pointing data were used to calculate a medium-resolution, controlled mosaic. Finally, the high-resolution mosaic calculated as described in Section 2.1 was registered on the controlled mosaic to improve its global accuracy and feature definition.

### **3. Enceladus map tiles**

The Enceladus atlas was produced in a scale of 1: 500,000 and consists of 15 tiles that conform to the quadrangle scheme proposed by Greeley and Batson (1990) and Kirk (1997, 2002, 2003) for large satellites (Fig. 3). A map scale of 1: 500,000 guarantees a mapping at the highest available Cassini resolution and results in an acceptable printing scale for the hardcopy map of 4.5 pixel/mm. The individual tiles were extracted from the global mosaic and reprojected, coordinate grids were superposed as graphic vectors and the resulting composites were converted to the common PDF-format using software that was originally developed for Mars maps, the Planetary Image Mapper (PIMap) (Gehrke et al., 2000). The equatorial part of the map ( $-22^{\circ}$  to  $22^{\circ}$  latitude) is in Mercator projection onto a secant cylinder using standard parallels at  $-13^{\circ}$  and  $13^{\circ}$  latitude. The regions between the equator region and the poles ( $-66^{\circ}$  to  $-21^{\circ}$  and  $21^{\circ}$  to  $66^{\circ}$  latitude) are projected in Lambert conic projection with two standard parallels at  $-30^{\circ}$  and  $-58^{\circ}$  (or  $30^{\circ}$  and  $58^{\circ}$ , respectively). The poles are projected in stereographic projection ( $-90^{\circ}$  to  $-65^{\circ}$  latitude and  $65^{\circ}$  to  $90^{\circ}$  latitude). The Mercator maps are  $72^{\circ}$  in longitude dimension, the Lambert maps  $90^{\circ}$ , and the poles  $360^{\circ}$ . The individual tiles overlap in the North-South direction by one degree, however no overlapping region is present in the East-West direction (see Fig. 3). We have produced the maps using the same scaling factors in overlapping regions at the matching parallels  $\pm 21.34^{\circ}$  and  $\pm 65.19^{\circ}$  latitude, 1.0461 and 1.0484 respectively (Snyder, 1987). Using this quadrangle scheme in the 1: 500,000 scale for Enceladus, we get the printed maps with the Mercator and Lambert projection in the same user-friendly size of 1050 mm width by 750 mm height, and the dimensions of the polar maps are 900 mm by 700 mm. We also added resolution maps and index maps for every individual tile, showing the image resolution, the image numbers and the location of the images for every map, respectively. Three map examples in different projections are shown in the Figures 4, 5, and 6.

The Cassini imaging team proposed 38 names for geological features, in addition to the 22 features already named by the Voyager team that are used in the maps. By international agreement, the features must be named after people or locations in the medieval Middle Eastern literary epic "One Thousand and One Nights". The locations and dimensions of all previously known features were measured again on the basis of the Cassini data and were corrected when necessary. Table IV shows a comparison of the locations measured on the basis of the Voyager data and the Cassini data for three craters. The nomenclature proposed by the Cassini-ISS team was approved by the IAU [<http://planetarynames.wr.usgs.gov/>].

The entire Enceladus atlas consisting of 15 map tiles will be made available to the public through the Imaging Team's website [<http://ciclops.org/maps>]. The map tiles will also be archived as standard products in the Planetary Data System (PDS) [<http://pds.jpl.nasa.gov/>].

### **4. Future Work**

The Cassini spacecraft will continue its imaging campaign through the Saturnian system. The next close flyby of Enceladus is scheduled for March 2008. Additional flyby opportunities are currently under investigation for the extended Cassini mission, which is expected to last until 2010. These upcoming flybys will help to replace the low-resolution parts of this atlas with

higher resolution image data and to enlarge the control point coverage. The northern part of Enceladus will be illuminated during the extended mission providing an opportunity to obtain high-resolution Cassini coverage of high northern latitudes.

**Acknowledgements:**

The authors gratefully acknowledge helpful discussions with J. Blue and R. Kirk (USGS) about the proposed nomenclature for Enceladus features and for reviewing the Enceladus atlas.

The authors also would like to thank Dave Williams (ASU) and another anonymous reviewer for their help to improve the paper.

## References

Hapke, B., 1993, *Theory of Reflectance Spectroscopy* (Topics in Remote Sensing, vol. 3), Cambridge University Press, Cambridge, p. 272.

Gehrke, S., Wählisch, M., Lehmann, H., Albertz, J., Roatsch, T., 2006, Generation of Digital Topographic Maps of Planetary Bodies, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Goa, Vol.36, Part 4, Commission IV, WG IV/7

Giese, B. Neukum, G., Roatsch, T., Denk, T. and Porco, C., 2006, Topographic modeling of Phoebe using Cassini images, *Planetary Space Science* 54, 1156 - 1166.

Greeley, R. and Batson, G., 1990, *Planetary Mapping*, Cambridge University Press.

Kirk, R., 1997, 2002, 2003, Presentations to Cassini Surfaces Working Group.

Kirk, R.L., Becker, T.L., Rosanova, T., Soderblom, L.A., Davies, M.E., Colvin, T.R., 1998, *Digital Maps of the Saturnian Satellites—First Steps in Cartographic Support of the Cassini Mission*, Jupiter after Galileo, Saturn before Cassini Conference. Nantes, France.

Porco, C. C. and 19 co-authors, 2004, Cassini Imaging Science: Instrument Characteristics and Anticipated Scientific Investigations at Saturn, *Space Science Review* 115, 363-497.

Porco, C. C. and 24 co-authors, 2006, Cassini Observes the Active South Pole of Enceladus, *Science* 311, 1393-1401.

Roatsch, T., Wählisch M., Scholten, F., Hoffmeister, A., Matz K.-D., Denk, T., Neukum G. Thomas, P., Helfenstein, P., and Porco, C., 2006, Mapping of the icy Saturnian satellites: First results from Cassini-ISS, *Planetary Space Sciences* 54, 1137 – 1145.

Snyder, J.P., 1987. *Map Projections – A Working Manual*. US Government Printing Office, Washington, p. 42.

Thomas, P. and 11 co-authors, 2006, Shapes of the Saturnian icy satellites and their significance, *Icarus*, in press.

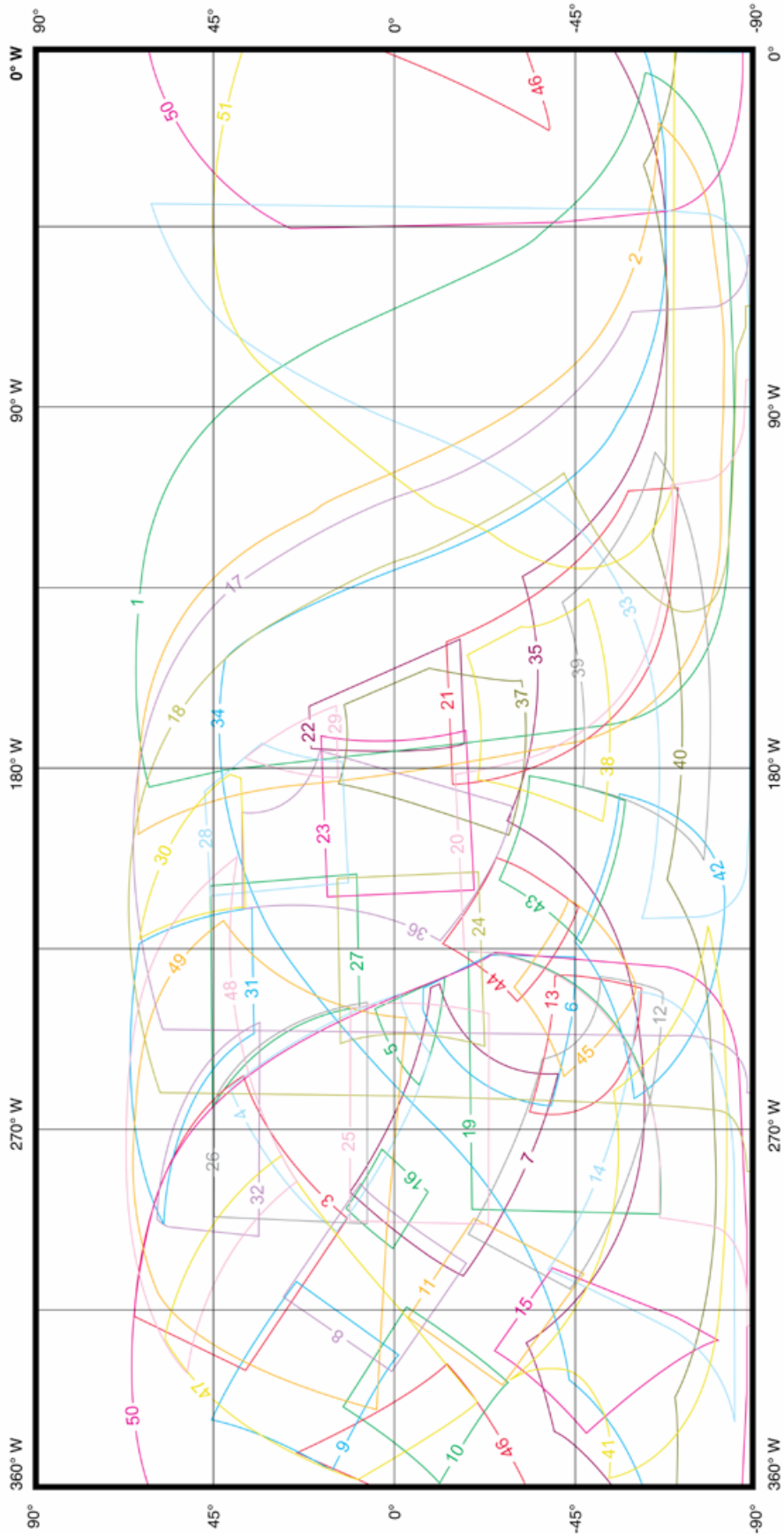


Figure 1: Global mosaic showing the location of the Cassini ISS images (see Table II). Mosaic is in simple cylindrical projection with latitude=0°, longitude=180° in the center.

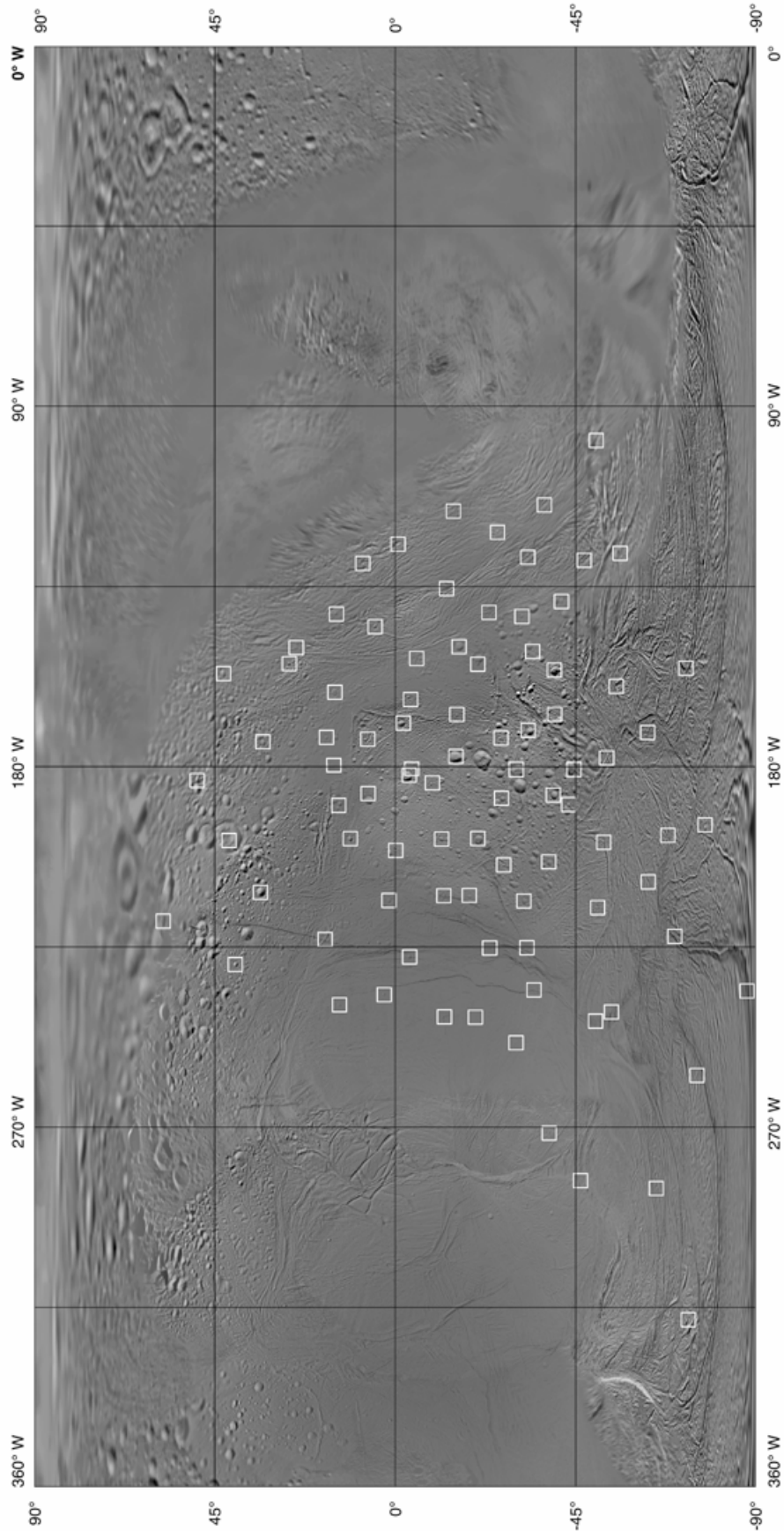


Figure 2: Global mosaic showing the location of the control points. Mosaic is in simple cylindrical projection with latitude=0°, longitude=180° in the center.



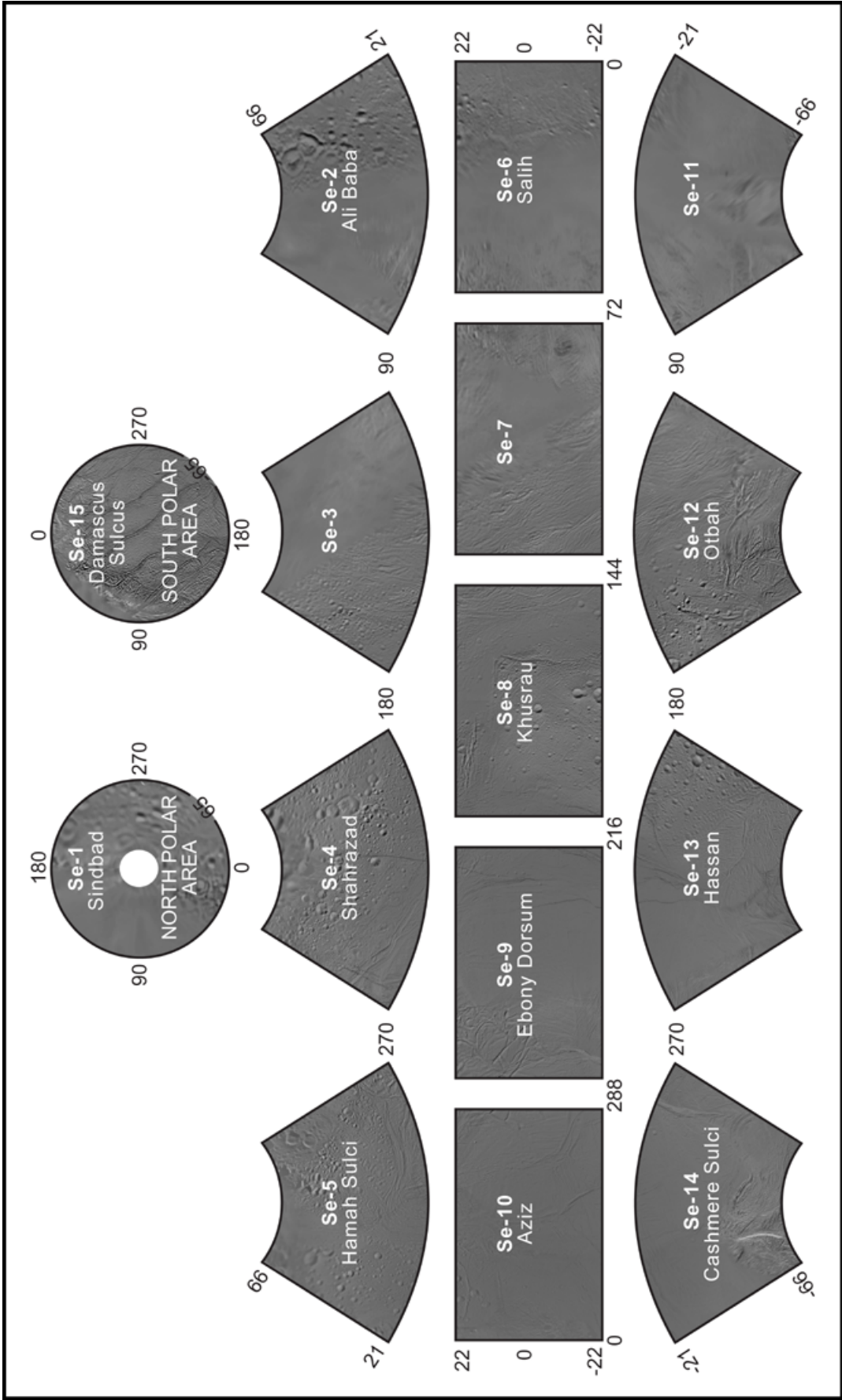
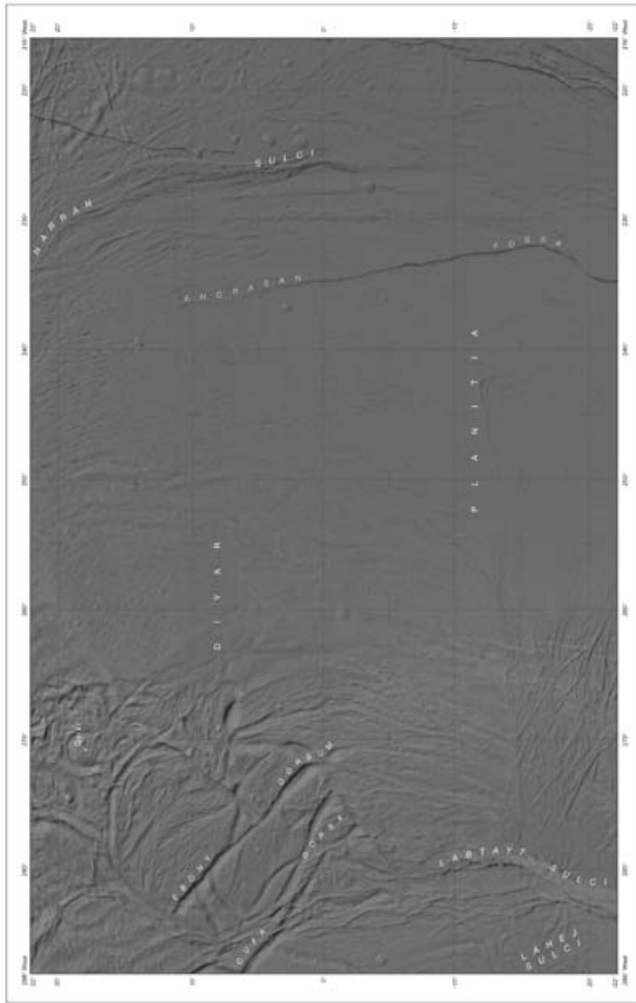
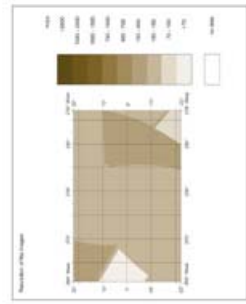
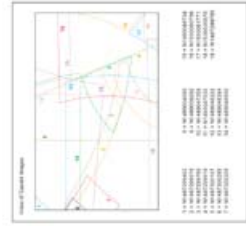
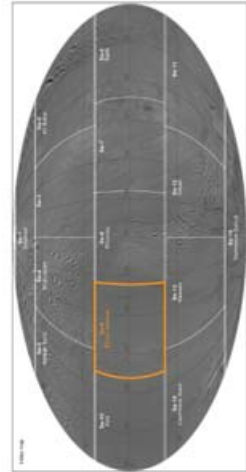


Figure 3: Quadrangle scheme filled with the 15 Enceladus tiles





Scale 1: 500,000  
0 10 20 30 km



**GENERAL NOTES**  
This map sheet is a part of a 1:500,000 scale mosaic of the entire surface of Enceladus, as shown in Figure 1 of this document. The mosaic is made from the Cassini spacecraft images acquired during the mission.

**MAP PROJECTION**  
The map uses the Universal Transverse Mercator (UTM) projection, Zone 18N. The datum is the Cassini 2004 datum.

**MAP PROCESSING**  
The map was processed using the Cassini 2004 data. The processing includes radiometric correction, geometric correction, and mosaicking.

**CONVENTIONS**  
The map uses the following conventions: brown for topographic relief, blue for water, and black for labels.

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**REFERENCES**  
This map sheet is based on the Cassini 2004 data. The following references provide additional information on the mission and the planet.

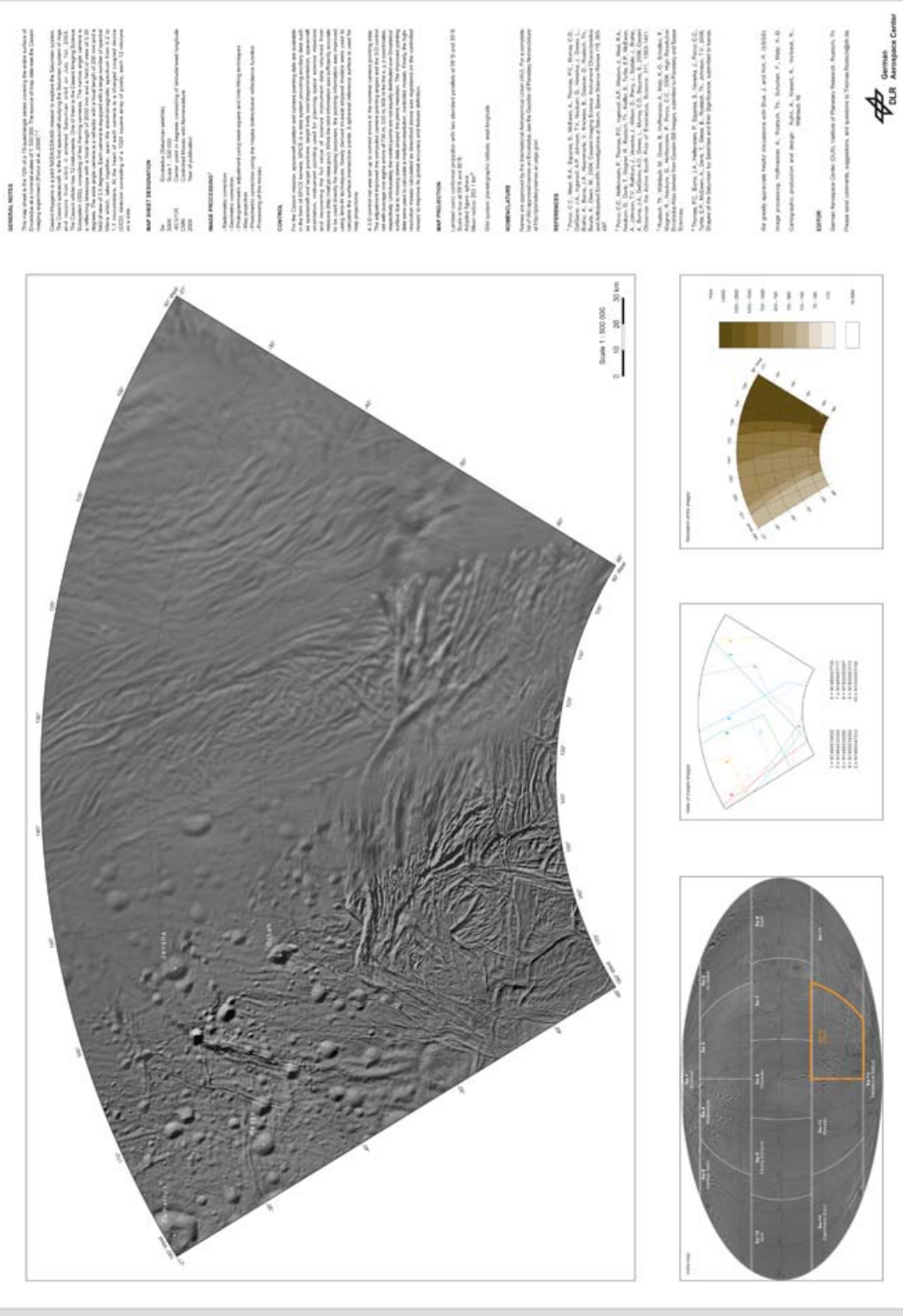
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**GENERAL NOTES**  
 This map sheet is the result of a 3-D topographic reconstruction of the entire surface of Enceladus, based on data from the Cassini spacecraft. The map is based on the Cassini spacecraft data from the Cassini Orbiter Mission (COM) and is derived from the Cassini Orbiter Mission (COM) data. The map is based on the Cassini Orbiter Mission (COM) data and is derived from the Cassini Orbiter Mission (COM) data. The map is based on the Cassini Orbiter Mission (COM) data and is derived from the Cassini Orbiter Mission (COM) data.

**MAP SHEET DESIGNATION**  
 Se 500K -43.5/135 CMN, 2006

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Table I

Cassini Enceladus flybys in 2005

<b>Flyby Date</b>	<b>Flyby Distance (km)</b>
17 February 2005	1263.5
09 March 2005	501.8
14 July 2005	173.0

Table II

Cassini images used for the mosaic

<b>Image number in fig. 1</b>	<b>Image name</b>	<b>Resolution (km/pixel)</b>	<b>Center latitude (degree)</b>	<b>Center longitude (WEST) (degree)</b>
1	N1484519630	2.184	5.24	85.37
2	N1484532352	1.444	7.24	90.78
3	N1487299402	0.177	42.07	295.58
4	N1487299578	0.170	18.99	263.86
5	N1487299765	0.163	-0.76	243.61
6	N1487299918	0.156	-23.93	250.00
7	N1487300107	0.148	-12.47	281.07
8	N1487300285	0.141	5.28	309.06
9	N1487300482	0.133	20.90	331.94
10	N1487300648	0.126	-6.54	335.74
11	N1487300854	0.118	-22.62	313.85
12	N1487301032	0.111	-39.37	286.38
13	N1487301209	0.104	-47.51	257.24
14	N1487301386	0.097	-60.21	299.94
15	N1487301590	0.088	-42.85	324.25
16	N1487302209	0.064	2.40	288.95
17	N1489034080	0.860	-0.45	157.15
18	N1489039292	0.559	1.28	173.85
19	N1489047359	0.188	-38.29	248.69
20	N1489047533	0.180	-39.14	202.65
21	N1489047708	0.173	-35.00	157.63
22	N1489047867	0.167	3.13	156.62
23	N1489048050	0.159	-0.32	192.31
24	N1489048222	0.152	-3.41	224.71
25	N1489048394	0.146	-5.77	255.47
26	N1489048550	0.139	24.59	258.65
27	N1489048724	0.132	26.31	224.88
28	N1489048898	0.125	28.43	193.25
29	N1489049072	0.118	30.93	161.39
30	N1489049404	0.105	53.43	196.82
31	N1489049580	0.098	50.97	237.40
32	N1489049756	0.091	45.20	264.82
33	N1489087177	0.991	0.48	130.16
34	N1500051528	0.617	-43.64	169.92
35	N1500056680	0.349	-72.47	147.16
36	N1500060756	0.147	-4.06	199.58
37	N1500060887	0.141	-14.13	174.12
38	N1500061010	0.135	-38.04	166.70
39	N1500061132	0.129	-61.99	154.72
40	N1500061253	0.123	-84.38	95.17
41	N1500061390	0.116	-68.34	295.81

42	N1500061512	0.110	-63.25	220.27
43	N1500061634	0.104	-42.39	200.67
44	N1500061771	0.097	-29.96	219.25
45	N1500061892	0.091	-45.46	233.84
46	N1500068930	0.250	15.39	21.60
47	N1500069083	0.257	36.78	340.68
48	N1500069258	0.266	82.81	341.29
49	N1536530570	0.386	46.15	277.22
50	W1487299765	1.616	1.43	315.99
51	N1490643112	8.800	-0.22	74.90

Table III

Images used for the least-squares adjustment of attitude data

<b>Image name</b>	<b>Resolution (km/pixel)</b>	<b>Center latitude (degree)</b>	<b>Center longitude (WEST) (degree)</b>
N1489029762	1.16	-0.49	145.41
N1489034080	0.86	-0.45	157.15
N1489039292	0.56	1.28	173.85
N1489047533	0.18	-39.14	202.65
N1500041648	1.22	-36.26	142.41
N1500051528	0.62	-43.64	169.92
N1500056680	0.35	-72.47	147.16
N1500056947	0.34	-28.26	154.94
N1500057234	0.32	-13.42	198.46
N1500057514	0.31	-50.81	244.17
N1516171253	0.93	0.00	243.62



Table IV

Comparison of Voyager and Cassini crater location

<b>Crater name</b>	<b>Voyager</b>		<b>Cassini</b>	
	<b>Latitude (degree)</b>	<b>Longitude (WEST) (degree)</b>	<b>Latitude (degree)</b>	<b>Longitude (WEST) (degree)</b>
Shahrazad	48.2	195.1	46.8	197.6
Dunyazad	42.6	196.5	41.7	197.8
Dalilah	52.9	246.4	52.0	244.8