Reference frames and mapping schemes of comet 67P

v2 (24 September 2015)

by

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on behalf of the OSIRIS 3D Working Group and the entire OSIRIS Team

In July 2014, ESA's Rosetta mission reached its final target, comet 67P/Churyumov-Gerasimenko (67P). Since then, the OSIRIS cameras onboard Rosetta have continuously acquired a huge set of image data of the nucleus at pixel scales of 10s of meters during approach, up to high-resolution OSIRIS NAC images with pixel scales down to a few decimeters [A1].

To establish compatibility among derived data and scientific results, the intention of this document is to propose a set of rotational parameters of 67P that defines a common reference frame for the variety of applications within the OSIRIS team, as well as a proposal for common use within the entire Rosetta team. The proposed definitions are in agreement with different investigations within the OSIRIS 3D group and respective results from OSIRIS NAC analyses using different image processing approaches, i.e. stereo-photogrammetry (SPG, [A2]) and stereo-photoclinometry (SPC, [A3,A4]). The proposal also considers results from other investigations outside the OSIRIS team, specifically stereo analysis and landmark tracking using NAVCAM and OSIRIS WAC images (STR, [A5a,b]). The following definition of reference frames and rotation parameters is based upon analyses of images that have been acquired during August and September 2014. Thus, and particularly because of the unpredictable stability of the rotation of a comet nucleus, the relevance of all definitions is limited to this time period and will be subject to continuing investigations and further refinements.

To a major extent, the content of this document is an excerpt of a recently accepted publication [A6] to which we explicitly refer for further details.

This document consists of four parts:

A)   the definition of the 67P reference frame and rotational parameters

B)   the definition of 67P body subsets

C)   the definition of 67P standard map parameters for cartographic/thematic mapping

Appendix)   Examples for standard maps of 67P[1]

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[1] PDS and PSA organized an independent peer review of this document on 30 April 2015. The review panel certified that the reference frame discussed in part A is in accordance with IAU guidelines. This version of the document includes additional editorial changes recommended by the review panel.

Part A: Definition of the 67P reference frame and rotational parameters

Spin axis orientation:

By OSIRIS-based SPG, SPC, and STR methods, as well as within orbit determination efforts using NAVCAM and OSIRIS WAC data, the mean orientation (RA/DEC) of the rotation (z-)axis of 67P's body-fixed frame has been determined consistently within 0.2° in RA and DEC (i.e. within ~5 m on the surface of 67P). From a brute-force-like analysis of SPG results for seperated epochs over an entire period of ~1 month (Aug 3 - Sep 3, 2014), a periodic variation of the Z-axis orientation, significantly improving the consistency of the stereo-phototogrammetric image block from the 5 m scale to the <=1 m scale, was determined. In this time range, the observations can be interpreted and expressed as a precession of 67P's rotation axis over a precession cone with a half-cone angle of 0.14° +/-0.02° (1σ), a precession period of ~10.7 d +/- 0.5 d (1σ), and a mean orientation of the rotation axis (center of the cone) of RA / DEC: 69.54° +/- 0.05° (1σ) / 64.11° +/- 0.03° (1σ).

In the notation of the NAIF SPICE planetary constants kernel (PCK) for the 67P frame (BODYID 1000012), this definition can be expressed as follows [A7]:

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BODY1000012_POLE_RA        = (69.54      0.      0.)
BODY1000012_POLE_DEC       = (64.11      0.      0.)
BODY1000012_NUT_PREC_RA    = (0.32       0.)
BODY1000012_NUT_PREC_DEC   = (0.14       0.)
BODY1000012_NUT_PREC_PM    = (-0.288     0.)
BODY1000012_NUT_PREC_ANGLES = (372.52    -1228878.50  0.      0.)
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The center of mass (COM) defines the origin of the nucleus of 67P. The COM and its position in the J2000 inertial frame is provided by ESA's 67P ephemeris kernel for the Rosetta mission (CORB_DV_*.BSP). ESA's Rosetta Mission Operation Report #184 (2014-11-03) states that the latest shift of 67P's COM of 7.2 m is foreseen to be final, and, in fact, it hasn't changed ever since. The uncertainty can thus be assumed to be <<10 meters.

Spin rate and zero-longitude definition:

Already during Rosetta's approach to 67P, a significant change of the spin rate of 67P compared to the pre-2009 perihelion passage was determined by analysis of light curves from unresolved OSIRIS images [A8] where a spin rate of the nucleus of 67P of 12.4043 h +/- 0.0007 h was proposed.

Based upon analyses of resolved OSIRIS image data of 67P that have been acquired during several

mapping campaigns, results from SPC, as well as from SPG confirm these light curve measurements within its error bars and provide a refined definition of 67P's spin rate, i.e. 12.4041 h +/- 0.0004 h, which is also in good agreement with ESA/RMOC results for the respective time period based upon NAVCAM and OSIRIS WAC image analysis (12.40428 h, resp. 12.40443 h, [A5a]). In the notation of NAIF SPICE PCK, the respective figure of this prograde spin rate is expressed as a W1 value of 696.543884683 °/d.

For the alignment of 67P's long equatorial (x-)axis with the greatest extension of 67P's figure, as well as for conformity of spherical coordinates that are based upon previous ESA/RMOC datasets (e.g. landmark coordinates), the zero-longitude definition using the W0 parameter is chosen as 114.69°. The respective NAIF SPICE PCK notation is:

BODY1000012_PM = (114.69   696.543884683   0.)
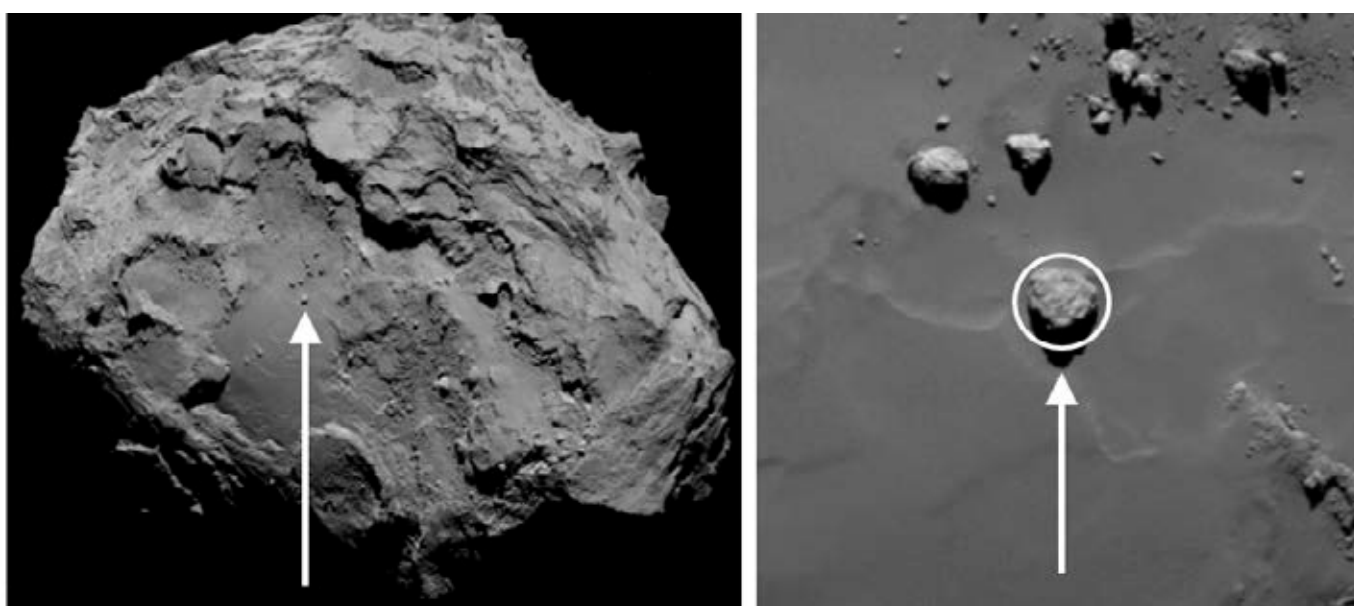
Fig. 1: Primary feature «Cheops» in Imhotep region. The context image (left) is a subset of NAC_2014-08-03T16.19.34.554Z_ID20_1397549400_F82, the close-up (right) is taken from NAC_2014-08-25T23.12.54.550Z_ID20_1397549700_F22.

Following the above definitions, the center of the prominent boulder-like feature «Cheops» in the Imhotep region (Fig. 1, about 50 m in diameter) on the big lobe of 67P has the following spherical coordinates (right-hand-rule eastern longitude / centric latitude / radial distance): 142.35° / -0.28° / 1,395 m, and will be used as a reference landmark with these fixed coordinates, assuming that its shape and position on 67P's surface is stable over the entire duration of the Rosetta mission. The herein defined reference system for 67P is called "Cheops reference frame" For continuous compatibility of any derived spherical or Cartesian body-fixed coordinates of 67P's surface features, further changes of 67P's PM definition (e.g. because of any variations of the spin rate (W1) during the mission) must ensure (by a respective adaptation of the W0 value) that Cheops' longitude and latitude remain fixed, at least to the current uncertainty of a few meters.

In order to further constrain the zero-longitude definition, we define the center of a secondary boulder-like feature near the equator on the opposite (small) lobe in the Hatmehit region (Fig. 2a) at 354.69° / 3.48° / 2,329 m, and the center of a third high-latitude boulder-like feature in the Seth region (Fig. 2b) at at 157.82°/ 71.99° / 1,099 m. Centric latitudes are also given herein in order to fix the full set of spherical coordinates. They are also in coincidence with latitudes in ESA/RMOC datasets. Region names taken from [A1,A9]).
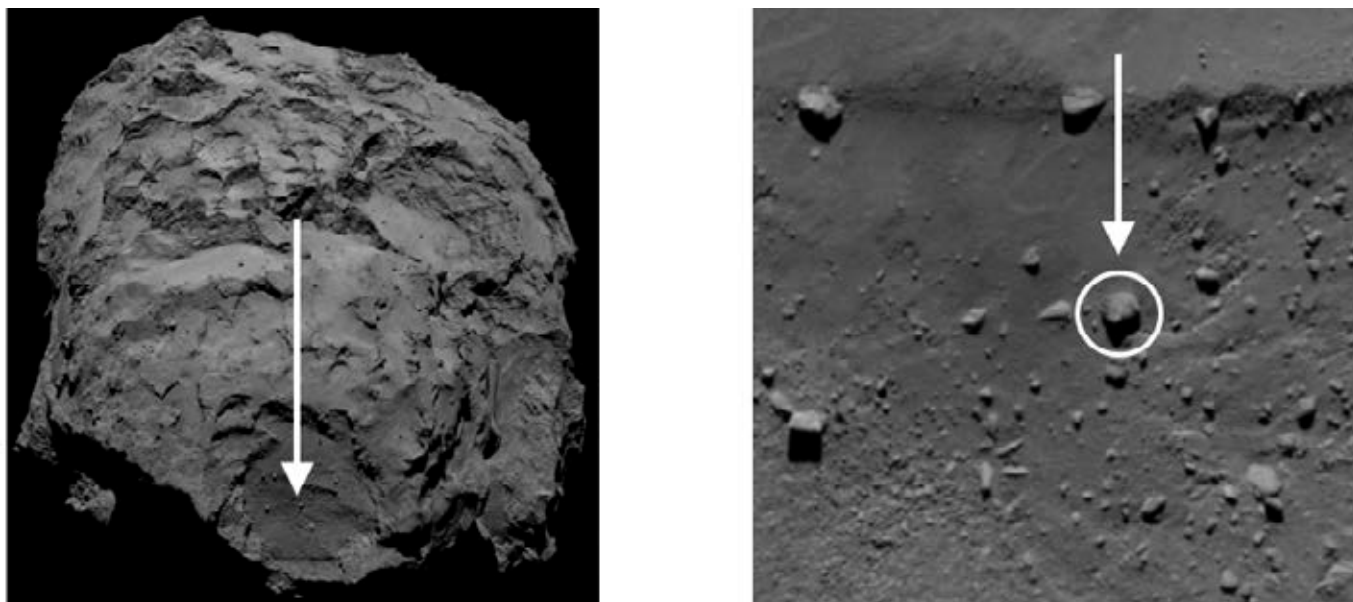
Fig. 2a: Secondary feature in Hatmehit region. The context image (left) is a subset of NAC_2014-08-06T01.19.14.554Z_ID20_1397549200_F22, the close-up (right) is subset of NAC_2014-08-26T04.42.54.592Z_ID20_1397549500_F22.
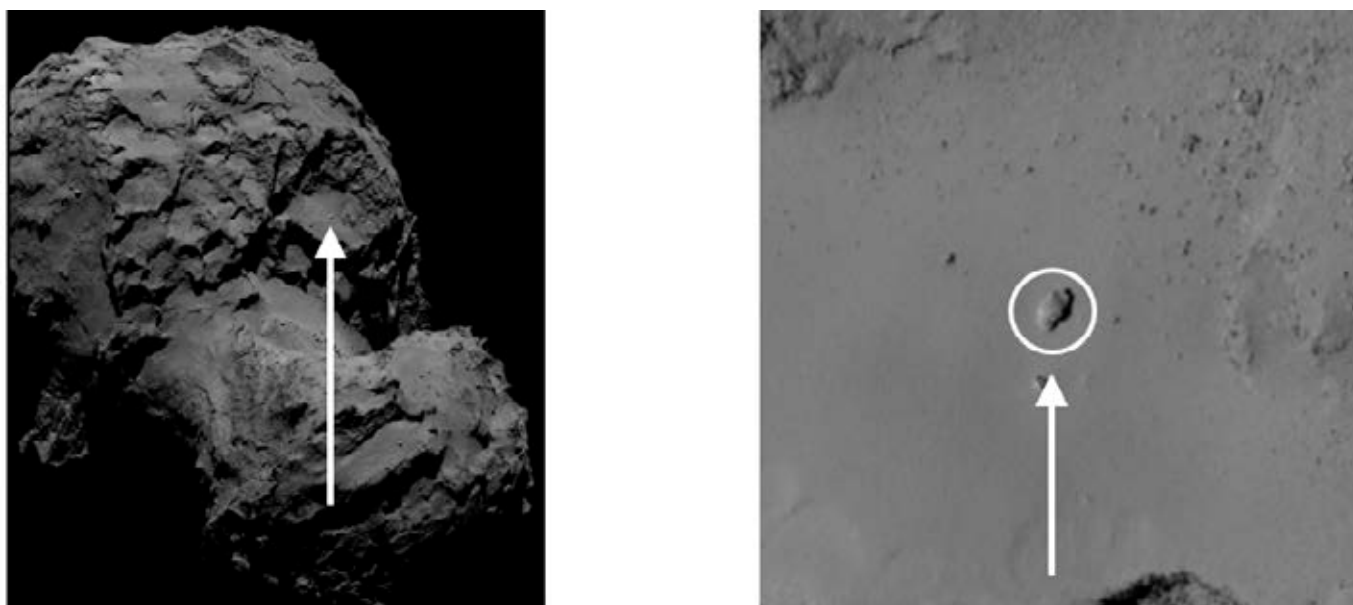
Fig. 2b: Third feature in Seth region . The context image (left) is a subset of NAC_2014-08-06T03.19.48.123Z_ID20_1397549900_F22, the close-up (right) is subset of NAC_2014-08-28T18.42.56.579Z_ID20_1397549500_F22.

Best-fit ellipsoid definition:

Best-fit ellipsoids have been retrieved from various 67P shape models. From analysis of the recent SPG-based model [A6], we extract the NAIF SPICE PCK notation for the planetary radii [in km]:

BODY1000012_RADII   = (2.40   1.55   1.20)

The entire set of defintions for the 67P frame (1000012) in NAIF SPICE PCK notation consists of the following data and are intended to be proposed to the IAU. Because of the already existing indications for changes of 67P's spin rate at the end of 2014 [A5b], all definitions will be explicitly time-tagged to the epoch before early September 2014 with possible minor updates from further refined analyses.

BODY1000012_POLE_RA   = (69.54   0.   0.)
BODY1000012_POLE_DEC   = (64.11   0.   0.)
BODY1000012_NUT_PREC_RA   = (0.32   0.)
BODY1000012_NUT_PREC_DEC   = (0.14   0.)
BODY1000012_NUT_PREC_PM   = (-0.288   0.)
BODY1000012_NUT_PREC_ANGLES   = (372.52   -1228878.50   0.   0.)
BODY1000012_PM   = (114.69   696.543884683   0.)
BODY1000012_RADII   = (2.40   1.55   1.20)

All investigations are based upon and relate to the 67P center-of-mass definition as provided by the Rosetta SPICE SPK kernel version 00130 (CORB/RORB_DV_075_01_____00130.BSP).

References Part A:
[A1] Sierks, H. et al. Science, 347, DOI: 10.1126/science.aaa1044, 2015.
[A2] Preusker, F. et al. PSS, 1 (66), DOI: 10.1016/j.pss.2012.01.008, 2012.
[A3] Gaskell, R. et al., MPS 43, 1049, 2008.
[A4] Jorda, L. et al. Icarus, 2015 (in preparation).
[A5a] ESA. RO-ESC-RP-5018, Issues 181-184, 2014.
[A5b] ESA. RO-ESC-RP-5018, Issues 190ff (confidential, for internal use), 2014/2015.
[A6] Preusker, F. et al. A&A (in press), 2015.
[A7] "SPICE PCK Required Reading"; latest version;
http://naif.jpl.nasa.gov/pub/naif/toolkit_docs/FORTRAN/req/pck.html.
[A8] Mottola, S. et al. A&A 569, L2, DOI: 10.1051/0004-6361/201424590, 2014
[A9] Thomas, N. et al. Science, 347, DOI: 10.1126/science.aaa0440, 2015.

Part B: Definition of 67P body subsets

Particularly for adequate cartographic mapping applications, it is necessary to sub-divide the two-body-like shape of 67P into separate entities. Otherwise there is no uniqueness in terms of latitude/longitude for many parts of the entire shape. Therefore, we propose to divide the shape into three entities: the small lobe (SL), the big lobe (BL) and the neck region (NR) in order to minimize multi-valued lat/lon areas. A local frame will be defined for each of these three entities. The local frames have their axes parallel to those of the main frame (see Part A of this document), but their center is translated with respect to the center of the 67P body-fixed frame. The Cartesian coordinates of the center of the three local frames are defined in the Table 1 below. The center coordinates have been calculated by the following steps:

   a) the part of the surface which has not yet been analysed as this document is being written (Apr 2015) have been cut from the recent SPC-based shape model to exclude them from the calculations below,

   b) the two lobes have been separated one from another, excluding also the neck region,

   c) the two lobe parts of the shape model has been fitted by ellipsoids, using as free parameters the center and the orientation of the respective ellipsoid as well as the radii of its three axes,

   d) the center of the neck region has been calculated by selecting manually three points of the surface considered to be in the median plane of the neck region. The three points are in a plane whose intersection with the surface of 67P defines a closed profile. The center of the neck region has been defined as the barycenter of the points included in this profile,

   e) finally, the center coordinates are slightly adjusted by minimizing apparent systematic deviations and asymmetry effects of the sub-lobe radii distribution within recent SPG-based lobe-wise shape models (compare with Part C and Appendix section).

The coordinates of the centers of all three entities have been used as centers for the respective reference frames. The coordinates in km have been rounded off to two digits. In Table 2, we propose explicit parameters for the two separation planes BL-NR and SL-NR. They are considered to be indicative and may be slightly adjusted with respect to the needs of specific applications.

Table 1. Cartesian coordinates of the centers of the local frames for the three entities (SL, BL and NR).

Entity	Proposed SPICE frame	Center coordinates		
		XC [km]	YC [km]	ZC [km]
67P global	67P_FIXED	0	0	0
67P big lobe	67P_FIXED_BL	-0.42	0.26	-0.06
67P small lobe	67P_FIXED_SL	1.48	-0.34	0.25
67P neck region	67P_FIXED_NR	0.66	-0.20	-0.30

Table 2. Indicative parameters of the two separation planes between the neck region (NR) and the two main lobes (BL and SL).

Separation plane BL-NR : $a \cdot X + b \cdot Y + c \cdot Z = d$

a	b	c	d
0.78706205	-0.55472785	0.26983386	0.29017997

Separation plane SL-NR: $a \cdot X + b \cdot Y + c \cdot Z = d$

a	b	c	d
-0.91856635	0.29122925	-0.26724800	-0.99968761
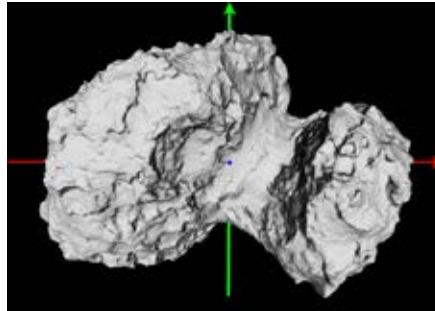
Fig. 3: North-polar view of global 67P shape model
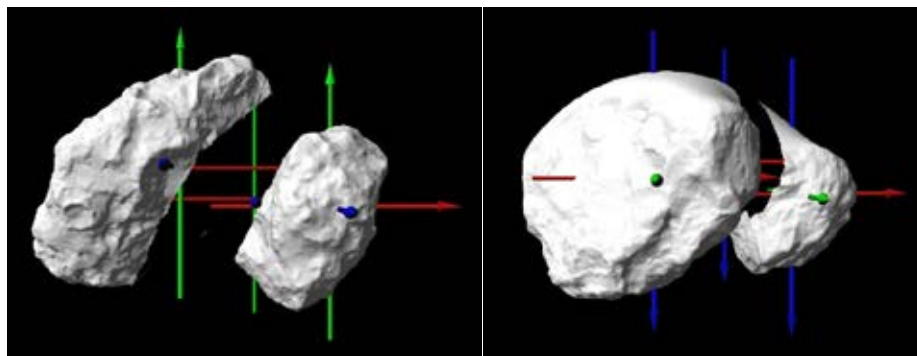
Fig. 4: Two views of Bl and SL entities (cuts are not final!)

The two lobe entities of the global 67P body (Fig. 3), as defined by the origin and x- (red), y- (green), and z-(blue) axis of all three entities, are displayed in Fig. 4. The neck region (NR) is the remaining part between the BL and SL entities.

Part C: Definition of 67P standard map parameters for cartographic/thematic mapping

For cartographic mapping, we propose standard map projections (see [C1]) and map reference bodies for the three entities of 67P. The use of reference spheres as map reference bodies is strongly recommended for the two lobes in order to avoid discrepancies between different implementations of map projections that are based upon non-spherical reference bodies (oblate spheroids or three-axial ellipsoids). For such non-spherical bodies, there are typically no unique definitions/implementations within commonly used mapping software.

For the two lobes we propose the Lambert Azimuthal map projection (authalic) as the standard map projection. For specific applications, the Stereographic map projection (conformal) is proposed as secondary options. For each of these two map projections we propose six different standard center coordinates in order to allow for adequate standardized mapping the six different aspects/sides of each lobe. For mapping entire lobes, we propose to use the Equidistant Cylindrical projection (aka Simple Cylindrical projection or Plate Carrée).

Since the extension of the specific tube-like neck region (NR) along its cylinder axis is short enough to be approximated by a sphere, the previously described map projections are applicable in almost the same way (except that those two aspects of NR that point towards the BL and SL entities, as well as entire NR equidistant cylindrical representations, are considered as obsolete.

Although there is no uniqueness for lat/lon over the entire body of 67P because of its very irregular shape, some applications may require global or hemisphere map representations. For these global maps of 67P, we propose to use the Equidistant Cylindrical map projection and north/south polar aspects of the Lambert Azimutal and Stereographic map projection.

For digital maps and for convenience of any re-scaling, the following standard m/pixel values are proposed: 0.25 m/pixel, 0.5 m/pixel, 1 m/pixel, 2 m/pixel, 4 m/pixel, 8 m/pixel, …

Table 2 summarises the definitions for the proposed standard map parameters. These definitions are not a formal prescription, other map parameters may be used if required for particular applications. Specific values for center longitudes were selected for the big lobe and the neck region so that the main features (the Imhotep region on the big lobe and the northern part of the neck region) appear at the center, resp. at the top of the maps. Table 2 also lists proposed dimensions of the reference spheres. The dimensions of the reference spheres for the different entities were chosen so that the maximum deviations of the topography from that sphere is minimized for each entity.

Table 2. Standard map reference body/dimensions & projections for all entities (Global 67P, SL.BL, NR)

Entity	Map reference body and dimensions	Map projection resp. map coordinates (cenlat/cenlon in °)
67P global GL	Sphere: Radius R: 1.5 km	Entire 67P: Equidistant Cylindrical Projection (cen_lat/cen_lon=0/90) Sub-maps : Primary/Standard: Lambert Azimuthal Projection Sub-maps : Secondary: Stereographic Projection 2 Sub-map aspects: (cen_lat/cen_lon 90/0, -90/0)
67P big lobe BL	Sphere: Radius R: 1.5 km	Entire lobe: Equidistant Cylindrical Projection (cen_lat/cen_lon=0/140) Sub-maps : Primary/Standard: Lambert Azimuthal Projection Sub-maps : Secondary: Stereographic Projection 6 Sub-map aspects: (cen_lat/cen_lon 90/0, -90/0, 0/50, 0/140, 0/230, 0/320)
67P small lobe SL	Sphere: Radius R: 1.1 km	Entire lobe: Equidistant Cylindrical Projection (cen_lat/cen_lon=0/0) Sub-maps : Primary/Standard: Lambert Azimuthal Projection Sub-maps : Secondary: Stereographic Projection 6 Sub-map aspects: (cen_lat/cen_lon 90/0, -90/0, 0/0, 0/90, 0/180, 0/270)
67P neck region NR	Sphere: Radius R: 1.0 km	Sub-maps : Primary/Standard: Lambert Azimuthal Projection Sub-maps : Secondary: Stereographic Projection 4 Sub-map aspects: (cen_lat/cen_lon 90/0, -90/0, 0/60, 0/240)

The nomenclature for each map is the following: 67P_RB_R_P_LAT_LON

RB = Reference body [GL, BL, SL, or NR]

R = Radius of body's reference sphere in m [1500, 1100, or 1000]

P = Projection [E = Equidistant Cylindrical, L = Lambert Azimuthal, S = Stereographic]

LAT = Center latitude of projection in deg [0 or 90]

LON = Center longitude of projection in deg [0, 90, …]

For illustration, examples for each of the proposed standard maps of 67P are presented within the appendix of this document.

References: [C1] Snyder, J.P. USGS Professional Paper: 1395, 1987.

Appendix:

Map examples (color-coded hill-shades relief map of the recent SPG-based shape model including the respective entity's latitude/longitude graticule) of the total of 21 proposed primary 67P standard maps: Multi-valued lat/lon areas in the northern hemisphere typically appear dark, multi-colored, and speckled.
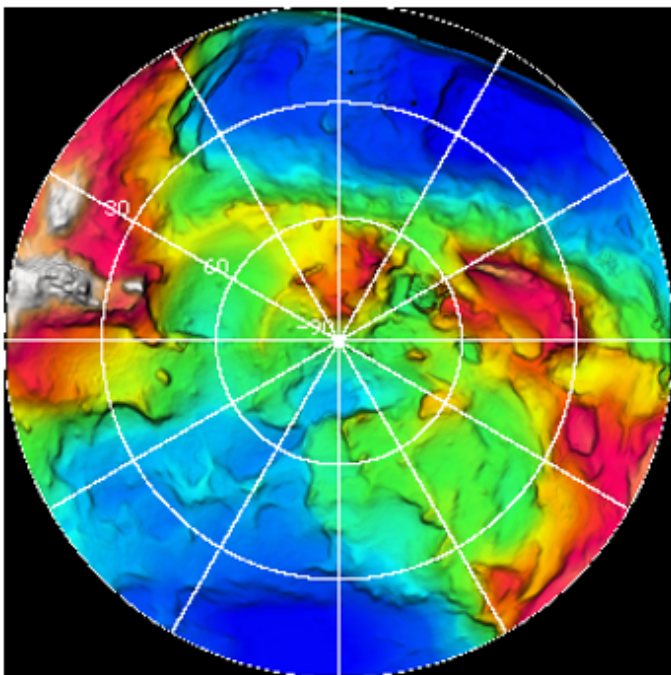
3 standard maps for GL (entire 67P)

If printed to A4 paper format, map scale is roughly 1:50K

color coding of heights above the 1,500 m reference sphere: blue = -1,000 m to red/white = 1,000 m)

(Black areas indicate currently not illuminated unmapped regions on 67P's southern hemisphere)
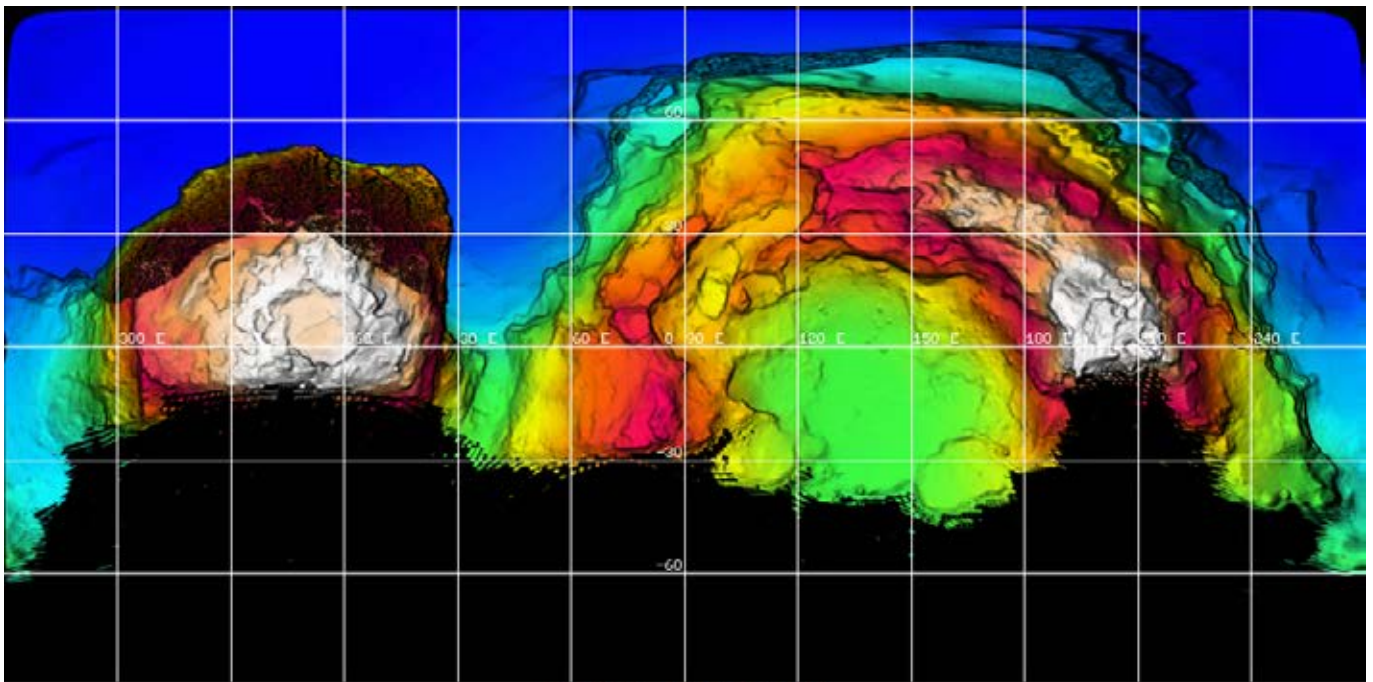
67P_GL_1500_E_0_90
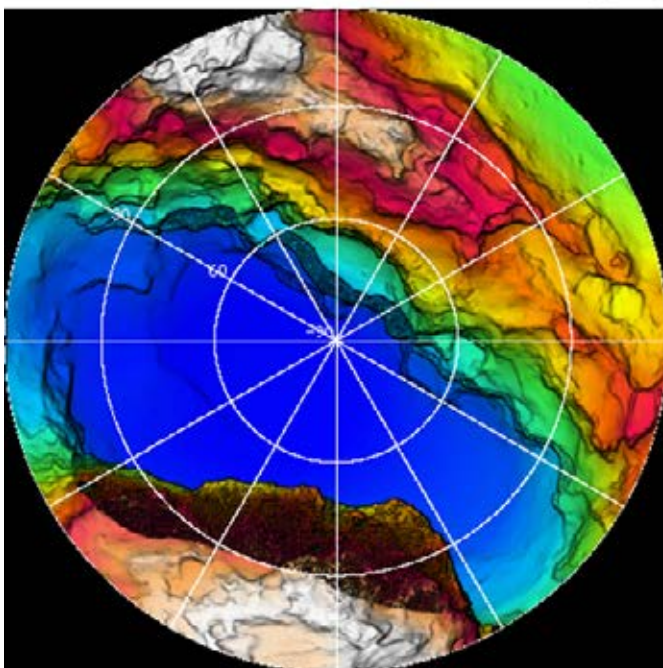
67P_GL_1500_L_90_0
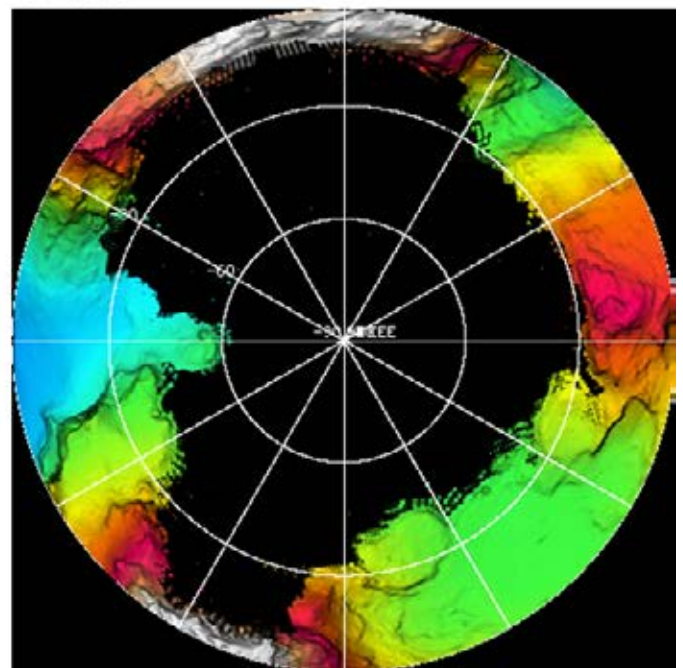
67P_GL_1500_L_-90_0

7 standard maps for BL (big lobe)

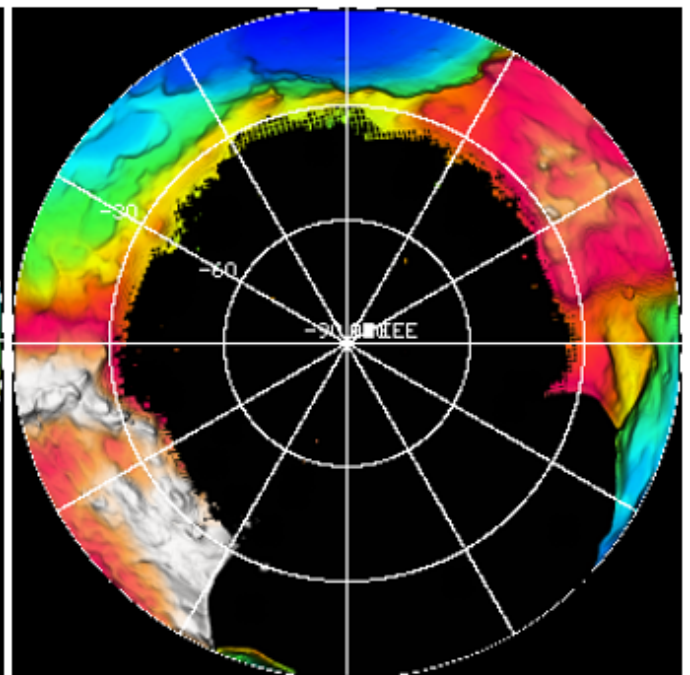**If printed to A4 paper format, map scale is roughly 1:50K**

color coding of heights above the 1,500 m reference sphere: blue = -1,000 m to red/white = 1,000 m)
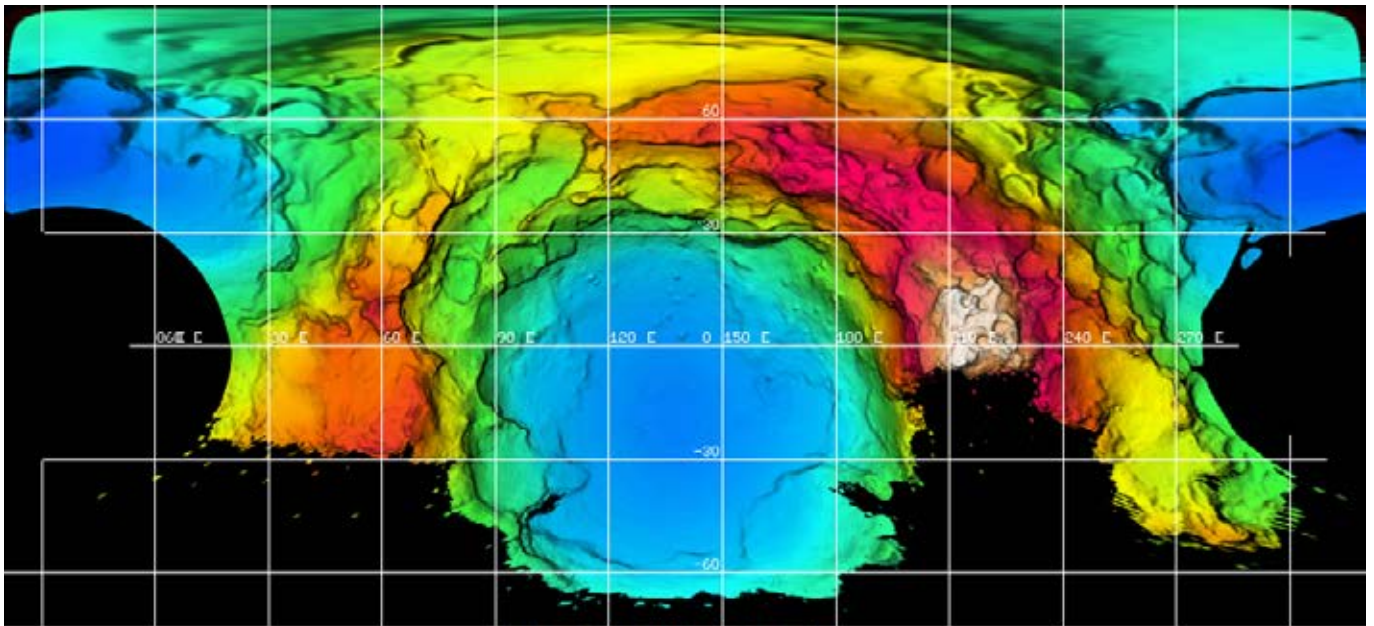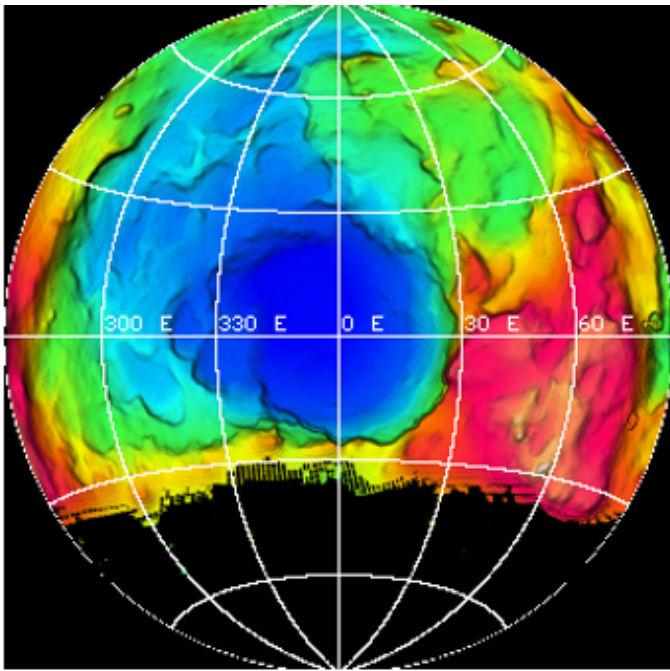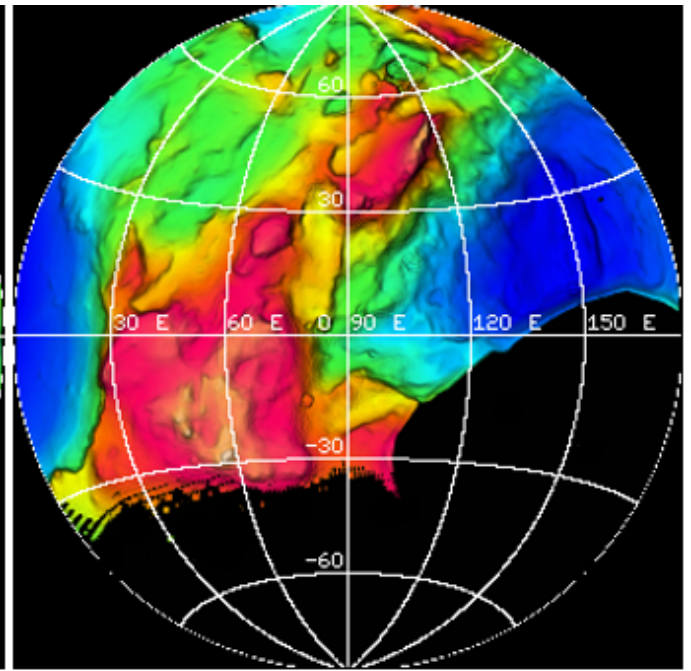

67P_BL_1500_E_0_140
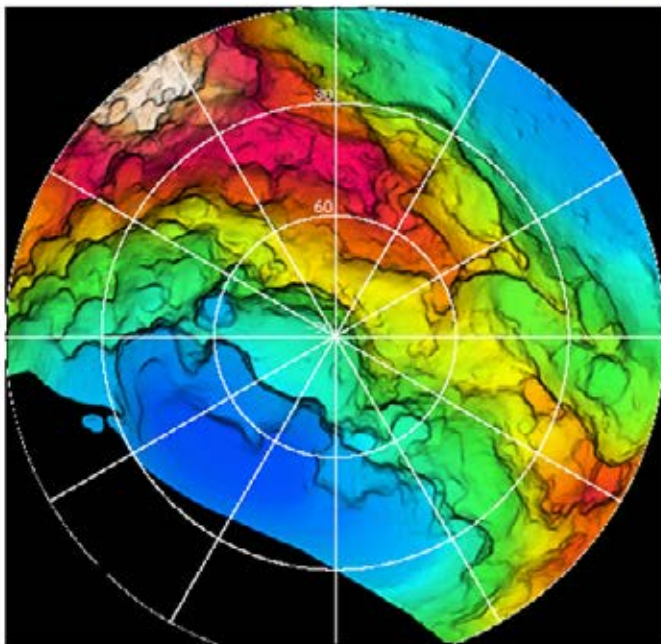
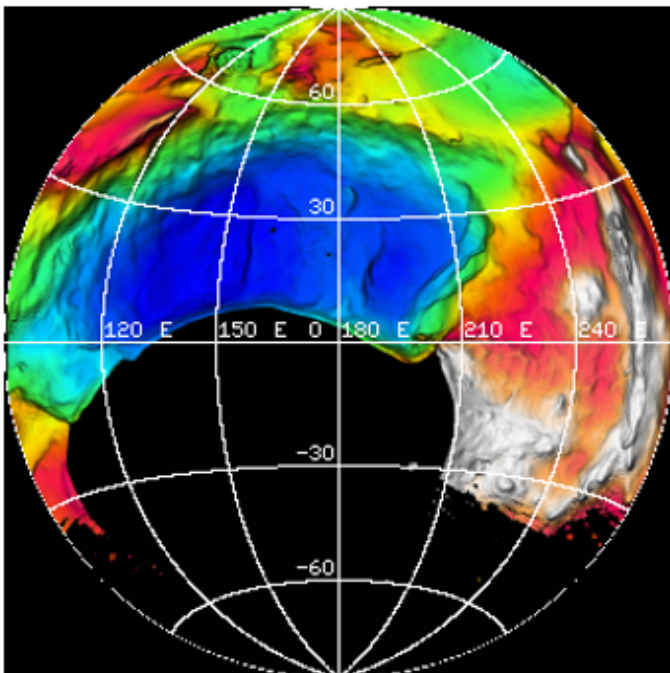
67P_BL_1500_L_90_0
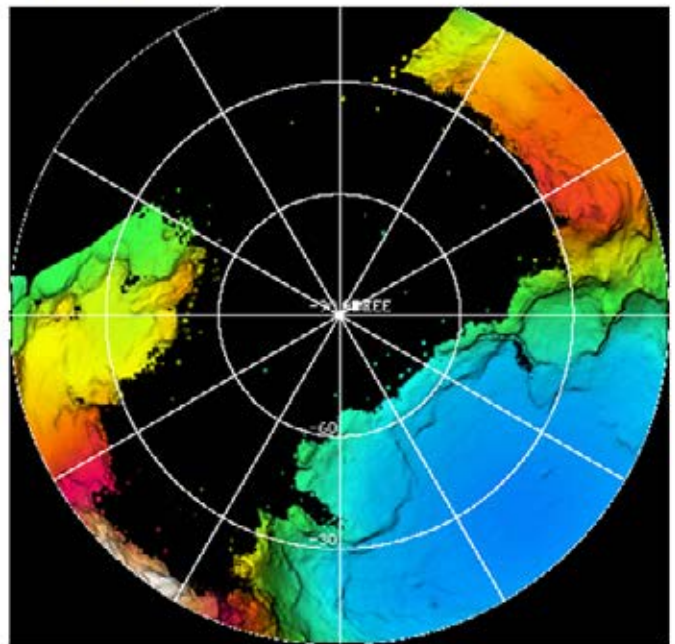
67P_BL_1500_L_-90_0

Black areas indicate currently not illuminated unmapped regions on 67P's southern hemisphere, as well as cut regions to adjacent sub-lobes (e.g. at left and right side in 67P_BL_1500_E_0_140).
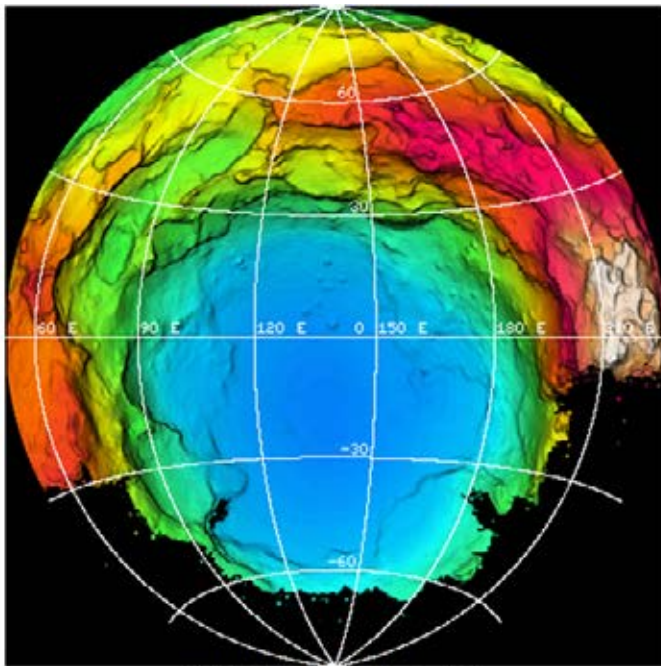
67P_BL_1500_L_0_140
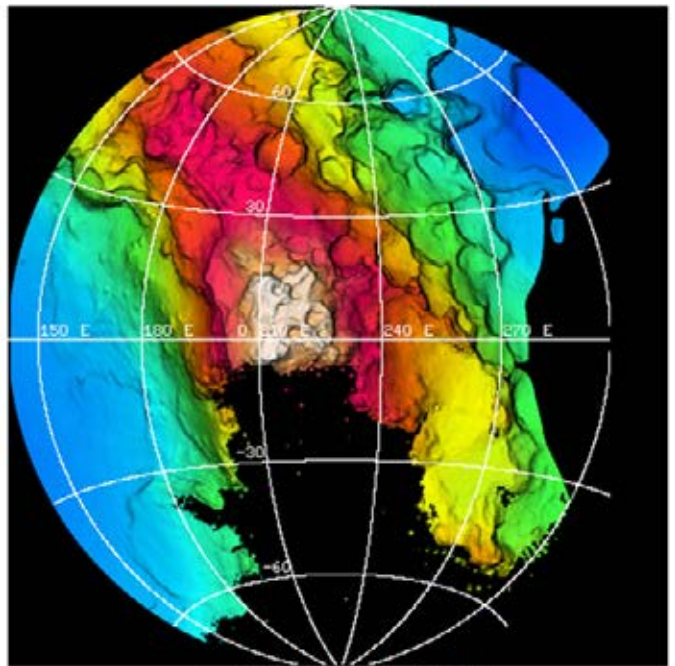
67P_BL_1500_L_0_230
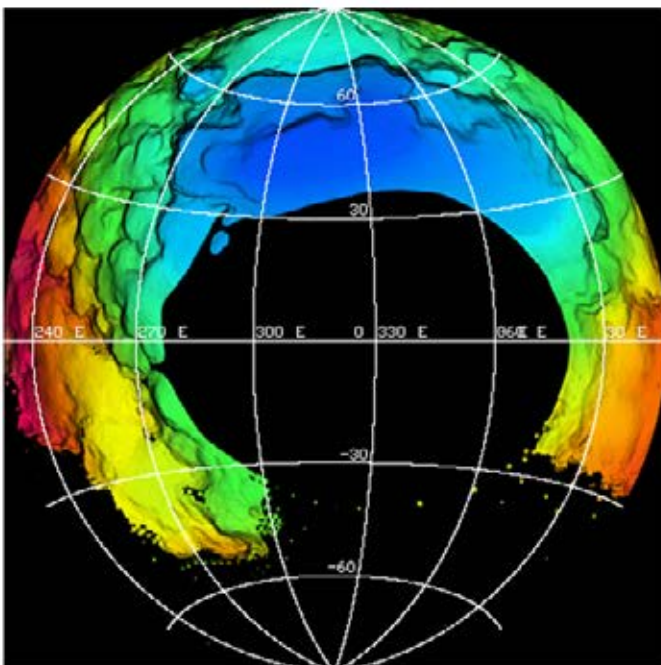
67P_BL_1500_L_0_320
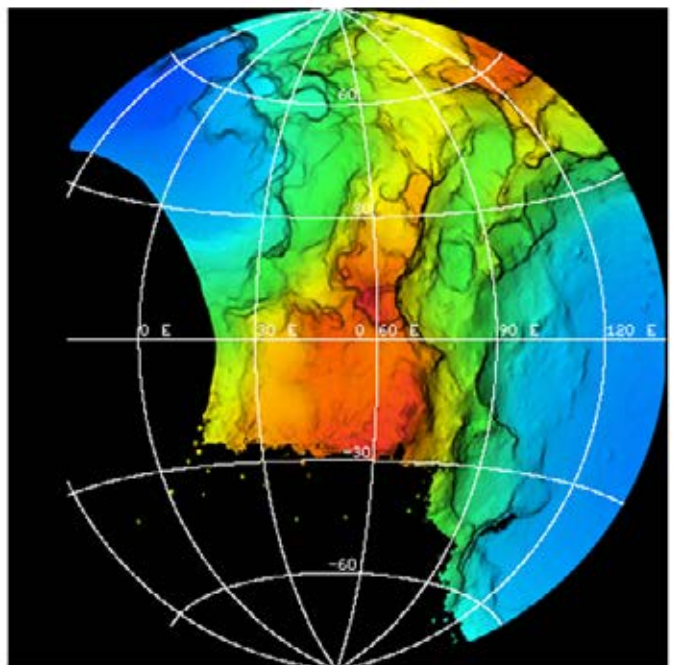
67P_BL_1500_L_0_50

7 standard maps for SL (small lobe)

If printed to A4 paper format, map scale is roughly 1:50K

color coding of heights above the 1,100 m reference sphere: blue = -300 m to red/white = 300 m)
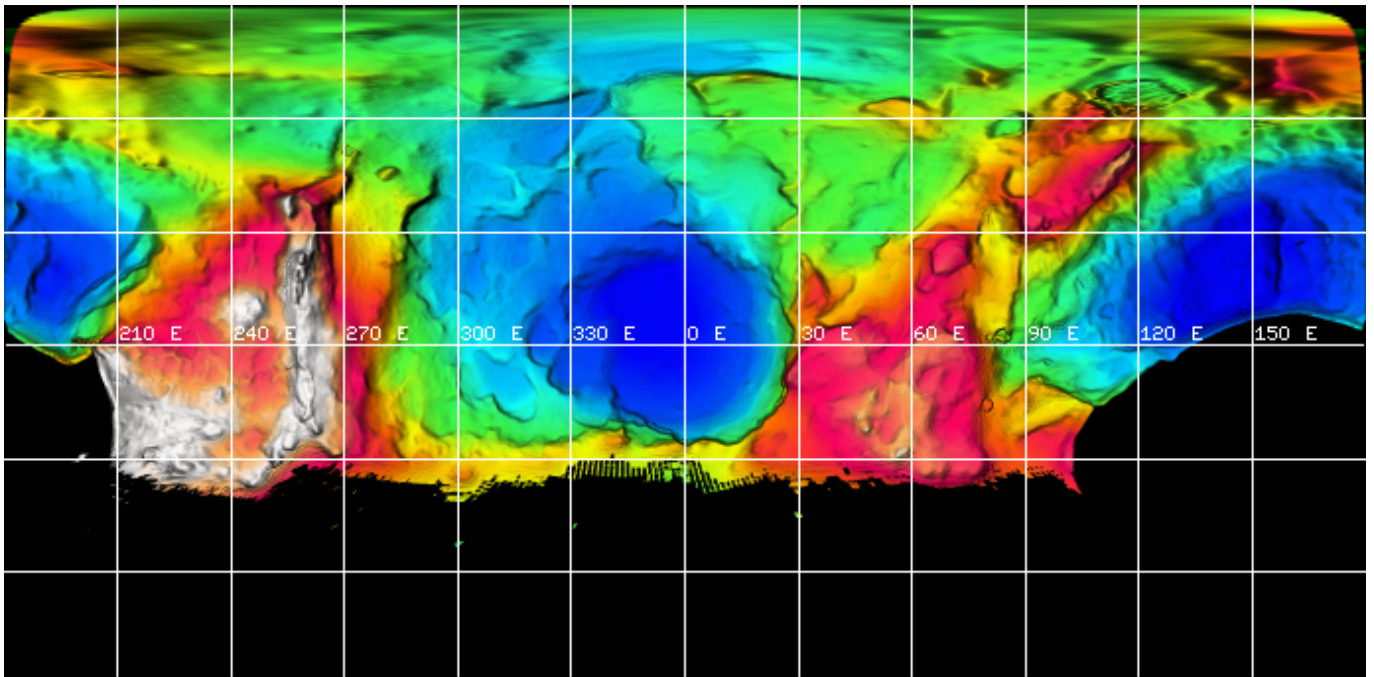
67P_SL_1100_E_0_0

67P_SL_1100_L_90_0   67P_SL_1100_L_-90_0

Black areas indicate currently not illuminated unmapped regions on 67P's southern hemisphere, as well as cut regions to adjacent sub-lobes (e.g. at left and right side in 67P_SL_1100_E_0_0).
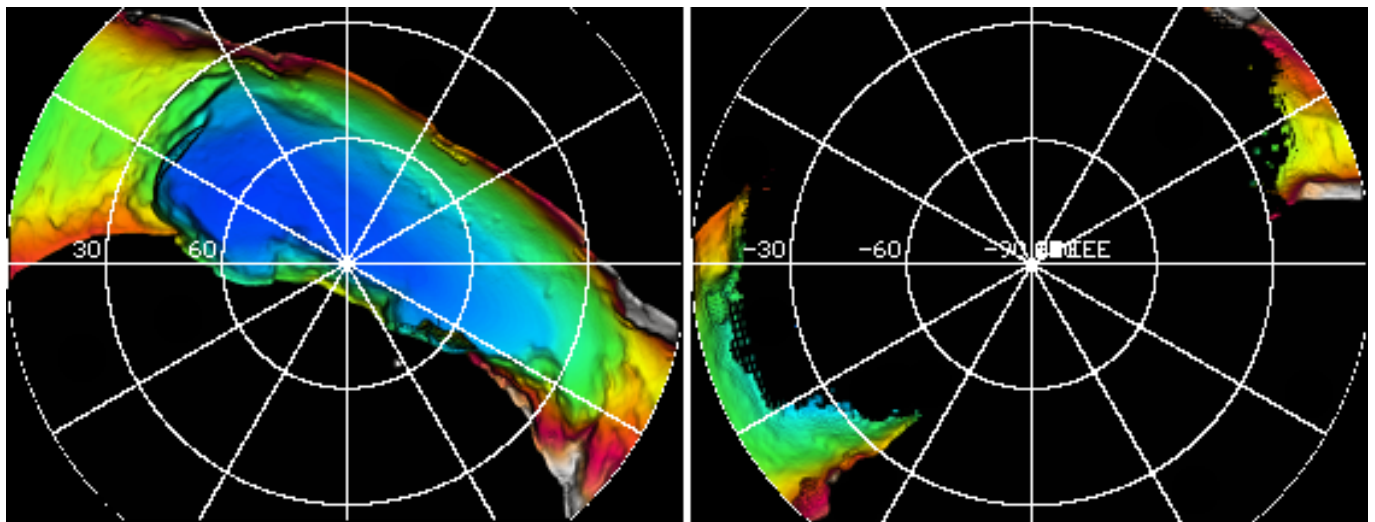
67P_SL_1100_L_0_0

67P_SL_1100_L_0_90

67P_SL_1100_L_0_180
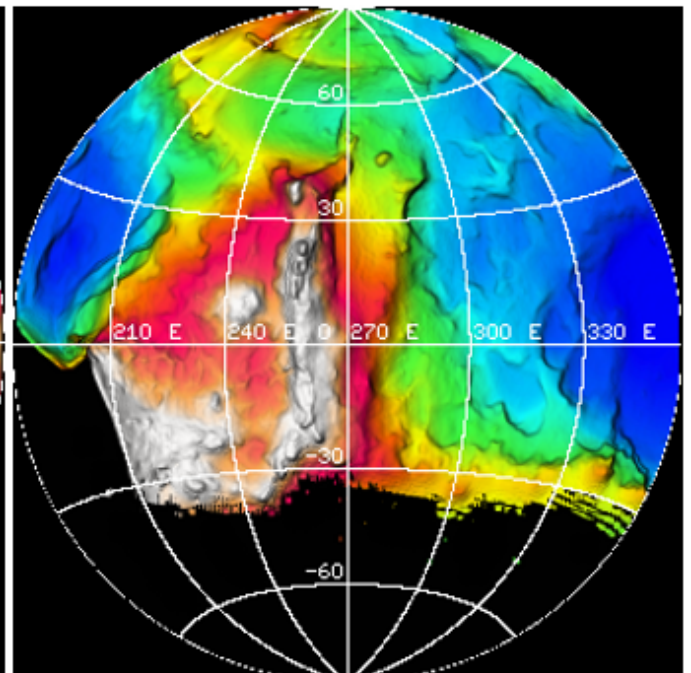
67P_SL_1100_L_0_270

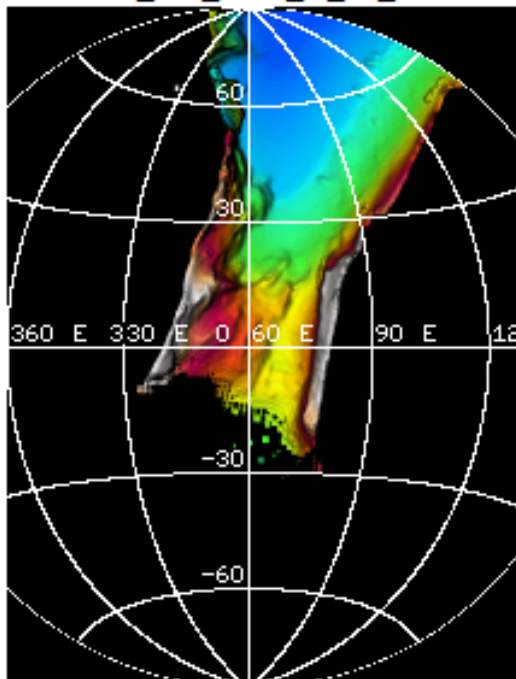**4 standard maps for NR (neck region)**

If printed to A4 paper format, map scale is roughly 1:50K

color coding of heights above the 1,000 m reference sphere: blue = -400 m to red/white = 400 m)
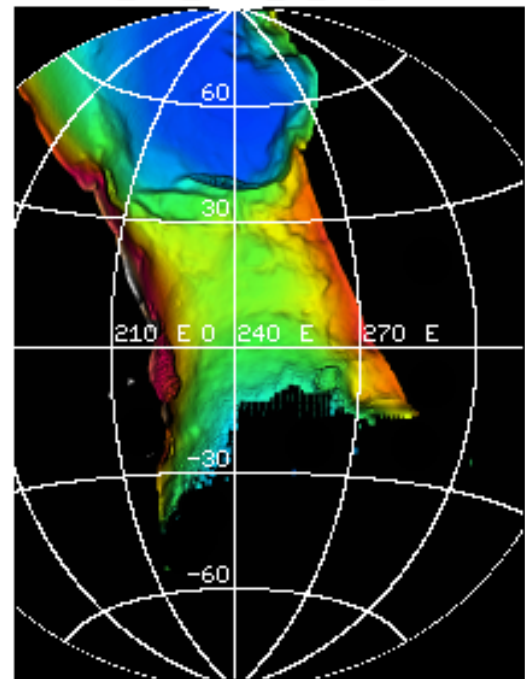

67P_NR_1000_L_90_0

67P_NR_1000_L_-90_0

67P_NR_1000_L_0_60

67P_NR_1000_L_0_240

Black areas indicate currently not illuminated unmapped regions on 67P's southern hemisphere, as well as cut regions to adjacent sub-lobes (e.g. at top right and bottom left side in 67P_NR_1000_L_90_0).