Proposal about
reference frames and mapping schemes of comet 67P/C-G
for common use within the Rosetta project
and for approval by the IAU

v1.1 (17 April 2015)

proposed 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 has reached its final target, comet 67P/Churyumov-Gerasimenko (C-G). 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].

For the establishment of compatibility among derived data and scientific results, the intention of this document is to propose a set of rotational parameters of C-G 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 of, i.e. stereo-photogrammetry (SPG, [A2]) and stereo-photoclinometry (SPC, [A3,A4]). The proposal also considers results from other investigations outside the OSIRIS team, i.e. results from stereo analysis and landmark tracking using NAVCAM and OSIRIS WAC image data [A5a,b]. The following definition of reference frames and rotation parameters is based upon analyses of image data 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 continuous investigations and further refinements.

To a major extent, the content of this document is an excerpt of a recently submitted publication [A6].

This document consist of four parts:

A) the definition of the C-G reference frame and rotational parameters

B) the definition of C-G body subsets

C) the definition of C-G standard map parameters for cartographic/thematic mapping

Appendix) Examples for standard maps of C-G

Part A: Definition of the C-G reference frame and rotational parameters (in standard NAIF SPICE PCK format for further approvement by the IAU)

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 C-G's body-fixed frame has been determined consistently within 0.2° in RA and DEC (i.e. within ~5 m on the surface of C-G). 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 C-G'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), 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/C-G frame (BODYID 1000012), this definition can be expressed as follows [A7]:

```
BODY1000012_POLE_RA          = (69.54                0.          0.)
BODY1000012_POLE_DEC         = (64.11                0.          0.)
BODY1000012_NUT_PREC_RA      = (0.32062676           0.          0.          0.)
BODY1000012_NUT_PREC_DEC     = (0.14                 0.          0.          0.)
BODY1000012_NUT_PREC_PM      = (-0.28788288          0.          0.          0.)
BODY1000012_NUT_PREC_ANGLES  = (372.518367261543 -1228878.504669825 0. 0. 0. 0. 0. 0.)
```

Spin rate and zero-longitude definition:

Already during Rosetta's approach to C-G, a significant change of the spin rate of C-G 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 C-G of 12.4043 h +/- 0.0007 h was proposed.

Based upon analyses of resolved OSIRIS image data of C-G 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 C-G'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 C-G's long equatorial (x-)axis with the greatest extension of C-G'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 choosen as 114.69°. The respective NAIF SPICE PCK notation is:

BODY1000012_PM = (114.69 696.543884683 0.)

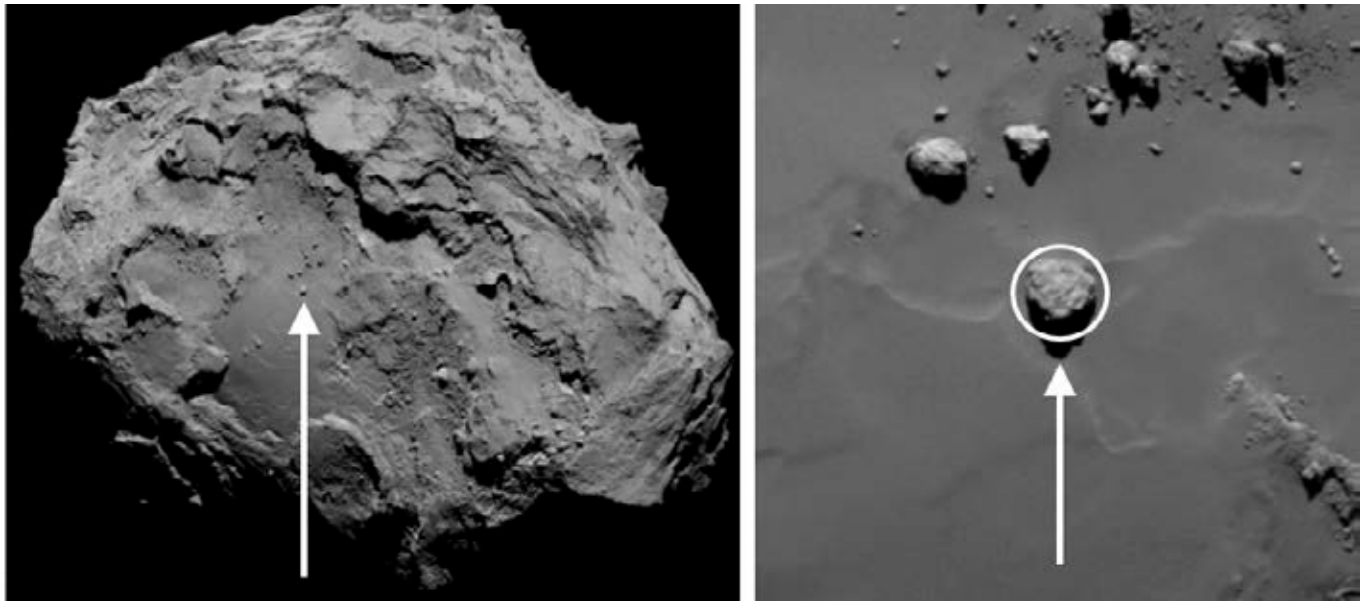


Fig. 1: Primary feature «Cheops» in Imhotep region. The context image (left) is a subset of NAC_2014-08-03T16.19.34.554Z_ID20_1397549400_F82, the close-up (right) is taken from NAC_2014-08-25T23.12.54.550Z_ID20_1397549700_F22.

Following the above definitions, the center of the prominent bolder-like feature «Cheops» in the Imhotep region (Fig. 1, about 50 m in diameter) on the big lobe of C-G has a longitude of 142.35° and a latitude of -0.28° and will be used as a reference landmark with these fixed coordinates, assuming that its shape and position on C-G's surface is stable over the entire duration of the Rosetta mission. The herein defined reference system for C-G is called "Cheops reference frame" For continuous compatibility of any derived spherical or Cartesian body-fixed coordinates of C-G's surface features, further changes of C-G'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 a longitude of 354.69° and a latitude of 3.48°, and the center of a third high-latitude boulder-like feature in the Seth

region (Fig. 2b) at a longitude of 157.82° and a latitude of 71.99°. Longitudes are right-hand-rule eastern longitudes. 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]).

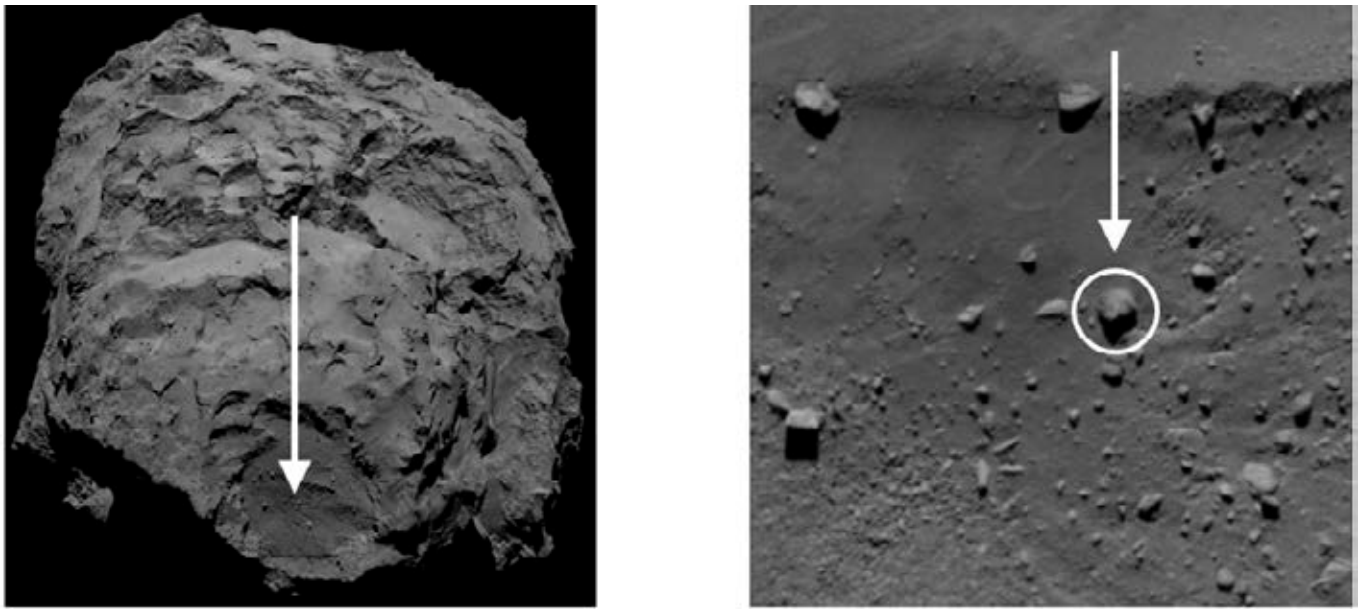


Fig. 2a: Secondary feature in Hatmehit region. The context image (left) is a subset of NAC_2014-08-06T01.19.14.554Z_ID20_1397549200_F22, the close-up (right) is subset of NAC_2014-08-26T04.42.54.592Z_ID20_1397549500_F22.

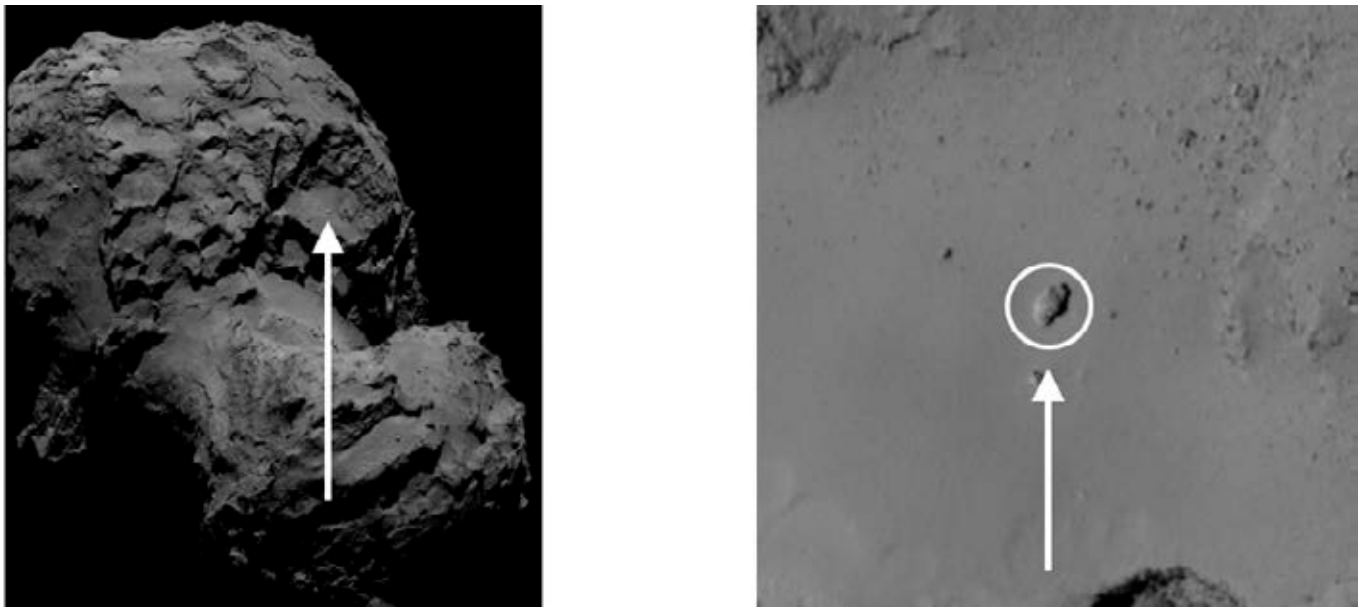


Fig. 2b: Third feature in Seth region . The context image (left) is a subset of NAC_2014-08-06T03.19.48.123Z_ID20_1397549900_F22, the close-up (right) is subset of NAC_2014-08-28T18.42.56.579Z_ID20_1397549500_F22.

Best-fit ellipsoid definition:

Best-fit ellipsoids have been retrieved from various C-G 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/C-G 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 C-G's spin rate at the end of 2014 [A5b], all definitions will be explicitely 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 = (0.32062676 0. 0. 0.)
BODY1000012_NUT_PREC_DEC = (0.14 0. 0. 0.)
BODY1000012_NUT_PREC_PM = (-0.28788288 0. 0. 0.)
BODY1000012_NUT_PREC_ANGLES = (372.518367261543 -1228878.504669825 0. 0. 0. 0. 0. 0.)
BODY1000012_PM = (114.48 696.543884683 0.)
BODY1000012_RADII = (2.18 1.31 1.08)

All investigations are based upon and relate to the C-G 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. To be submitted to PSS in April 2015.
[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. submitted to A&A in April 2015.
[A7] Personal communication with N. Bachman (JPL/NAIF), 2014.
[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 C-G body subsets

Particularly for adequate cartographic mapping applications, it is necessary to sub-divide the two-body-like shape of C-G 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 in three entities: the small lobe (SL), the big lobe (BL) and the neck region (NR). A local frame will be defined for each of these three entities. Local frames have their three axes parallel to those of the main C-G body-fixed frame (see Part A of this document), but their center is translated with respect to the center of the C-G 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 C-G 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]**
C-G global	67P/C-G_FIXED	0	0	0
C-G big lobe	67P/C-G_FIXED_BL	-0.42	0.26	-0.06
C-G small lobe	67P/C-G_FIXED_SL	1.48	-0.34	0.25
C-G neck region	67P/C-G_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 : $a \,.\, X + b \,.\, Y + c \,.\, Z = d$			
a	*b*	*c*	*d*
0.78706205	-0.55472785	0.26983386	0.29017997
Separation plane SL-NR: $a \,.\, X + b \,.\, Y + c \,.\, Z = d$			
a	*b*	*c*	*d*
-0.91856635	0.29122925	-0.26724800	-0.99968761

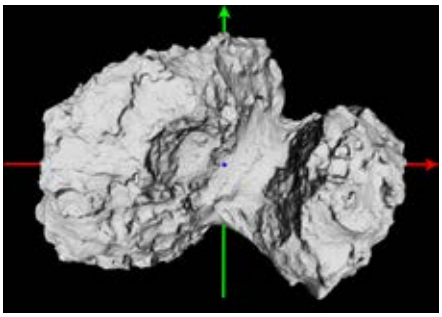


Fig. 3: North-polar view of global C-G shape model

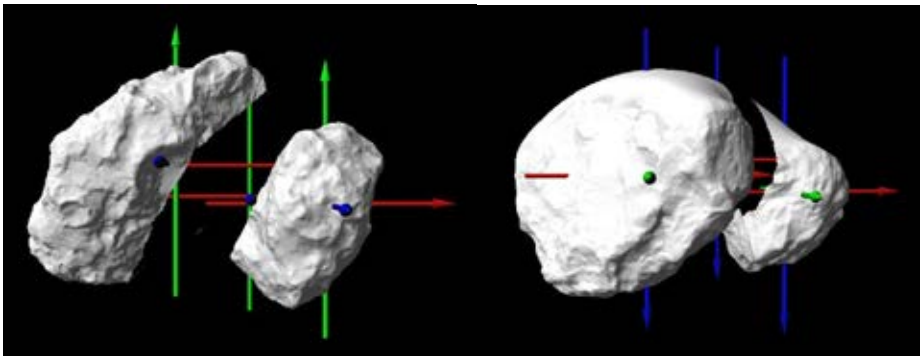


Fig. 4: Two views of Bl and SL entities (cuts are not final!)

The two lobe entities of the global C-G 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 C-G 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 C-G. 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 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 representations, are considered as obsolete.

Although there is no uniqueness for lat/lon over the entire body of C-G because of its non star-like shape, some applications may require global or hemisphere map representations. For these global maps of C-G, we propose to use the Eqidistant 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.

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

Entity	**Map reference body and dimensions**	**Map projection resp. map coordinates (cenlat/cenlon in °)**
C-G global GL	Sphere: Radius R: 1.5 km	Entire C-G: Equidistant 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)
C-G big lobe BL	Sphere: Radius R: 1.5 km	Entire lobe: Equidistant 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)
C-G small lobe SL	Sphere: Radius R: 1.1 km	Entire lobe: Equidistant 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)
C-G 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, 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 C-G are presented within the appendix of this document.

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

Appendix:

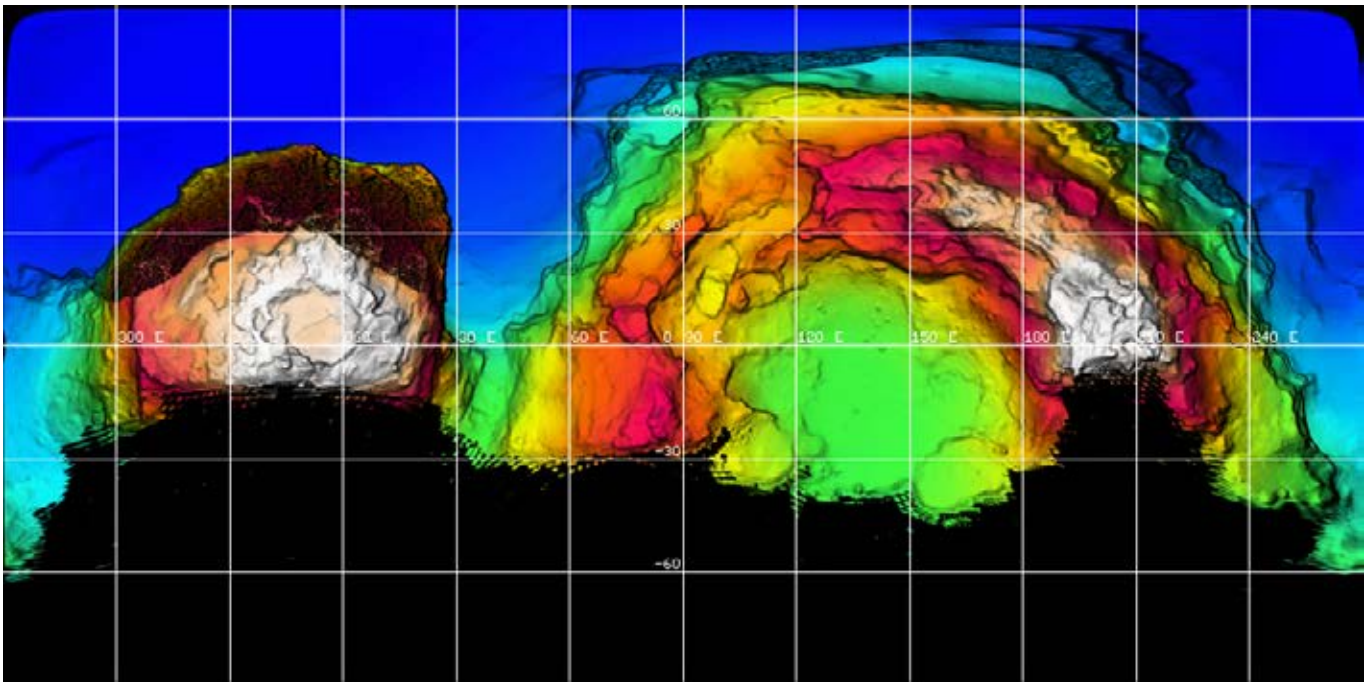
Map examples (color-coded hill-shades relief map of the recent SPG-based shape model including the respective entity's latitude/longitude graticule) of the total of 21 proposed primary C-G standard maps:

3 standard maps for GL (entire C-G)

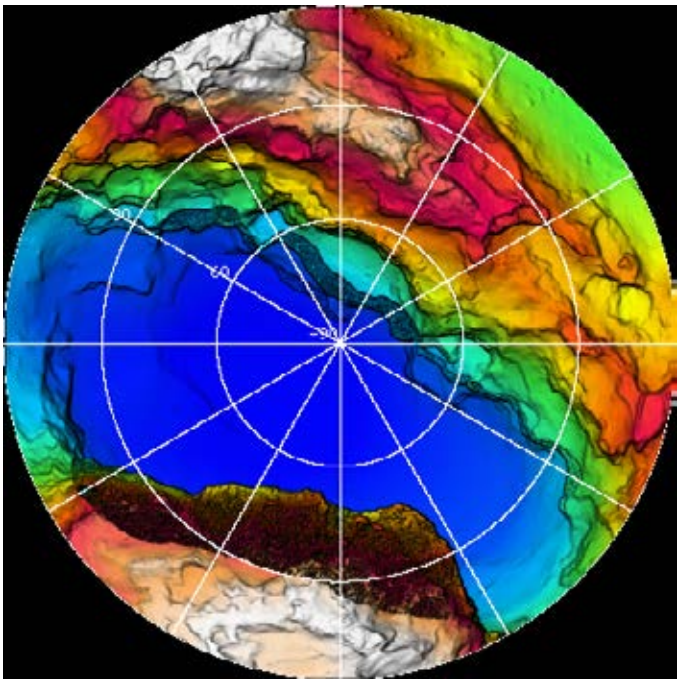
If printed to A4 paper format, map scale is roughly 1:50K

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 C-G's southern hemisphere)



67P_GL_1500_E_0_90



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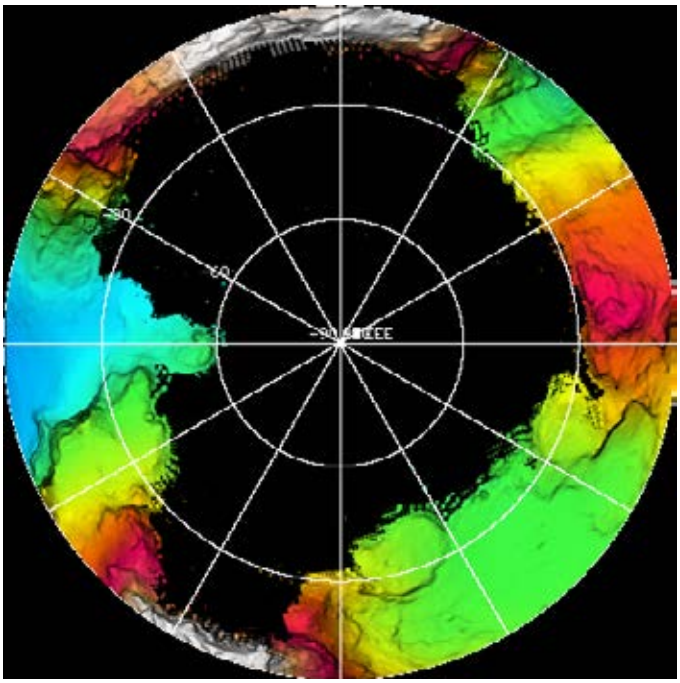
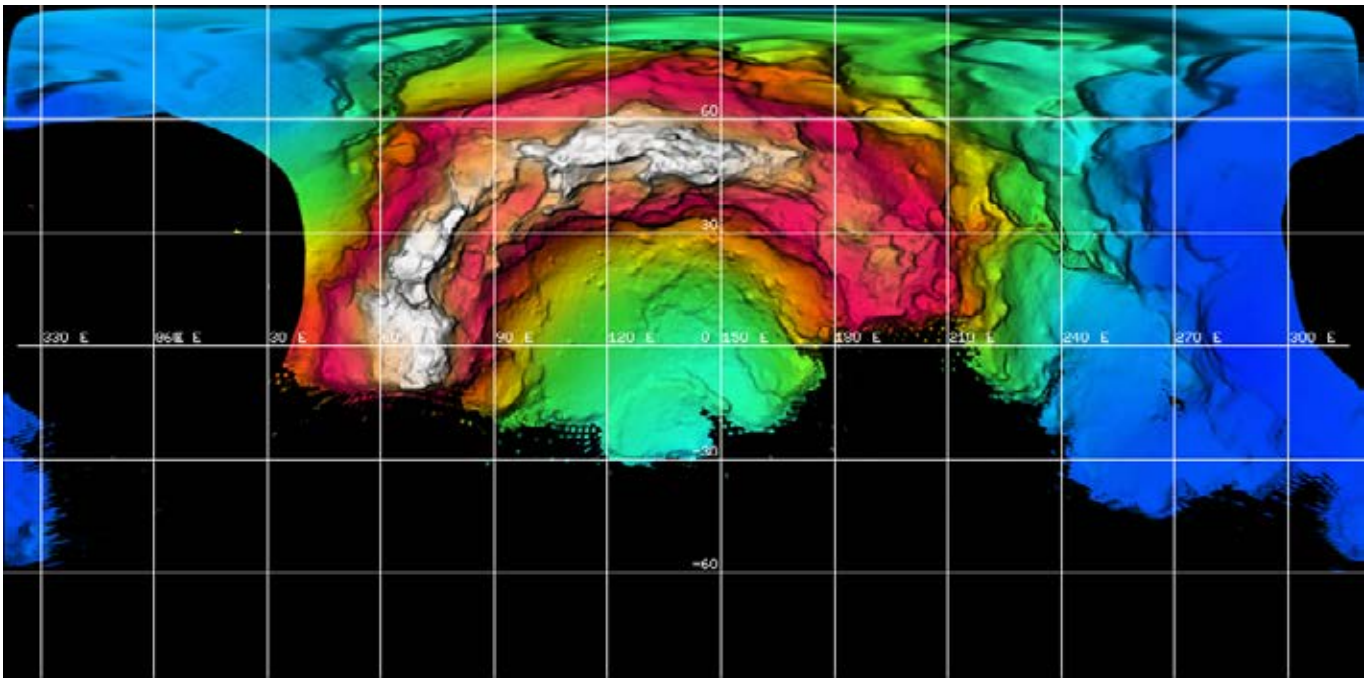


67P_GL_1500_L_-90_0

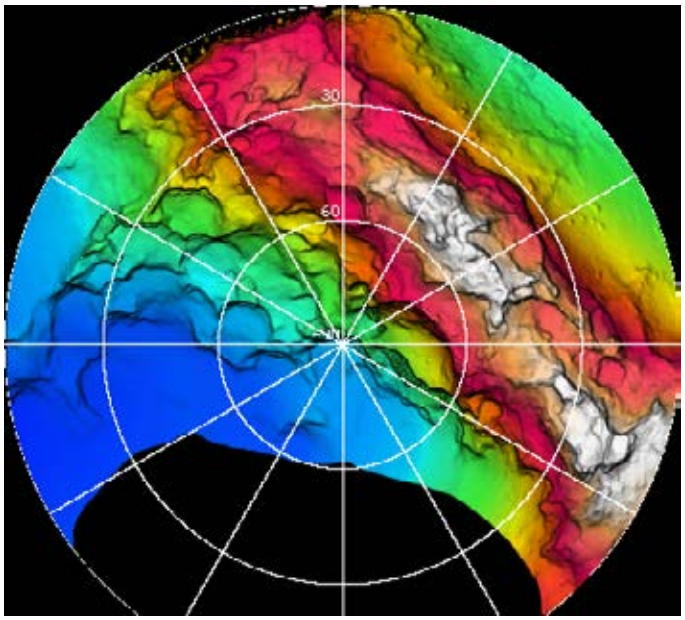
7 standard maps for BL (big lobe)

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

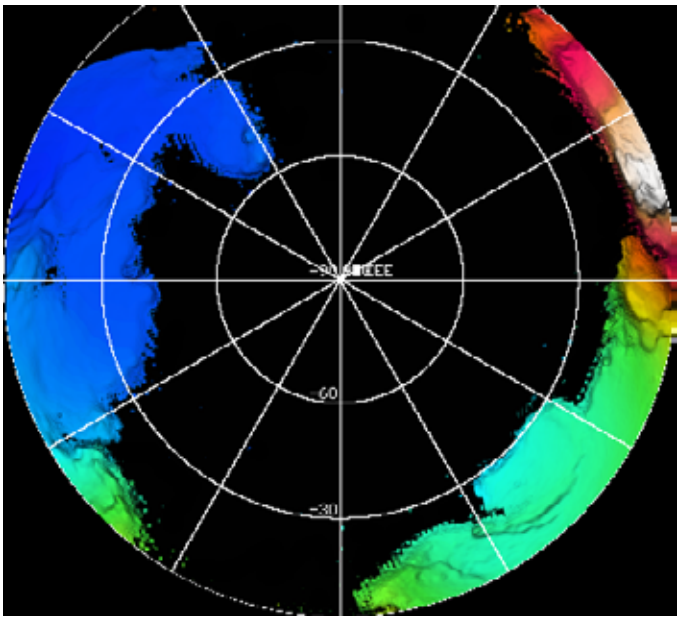
color coding of heights above the 1,500 m reference sphere: blue = -1,000 m to red/white = 1,000 m)



67P_BL_1500_E_0_140

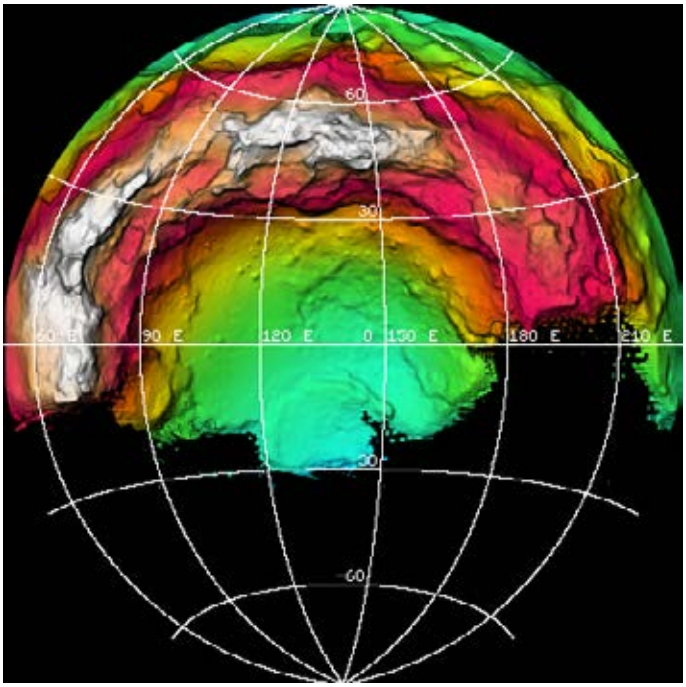


67P_BL_1500_L_90_0

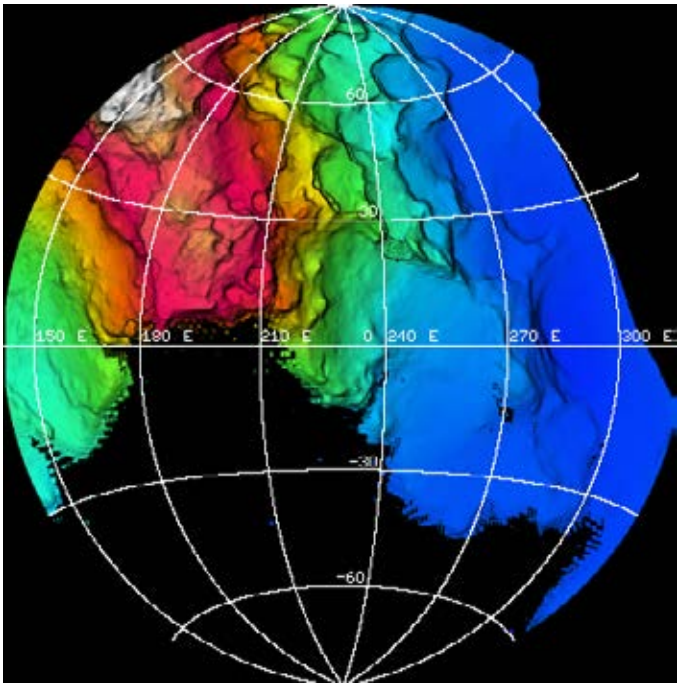


67P_BL_1500_L_-90_0

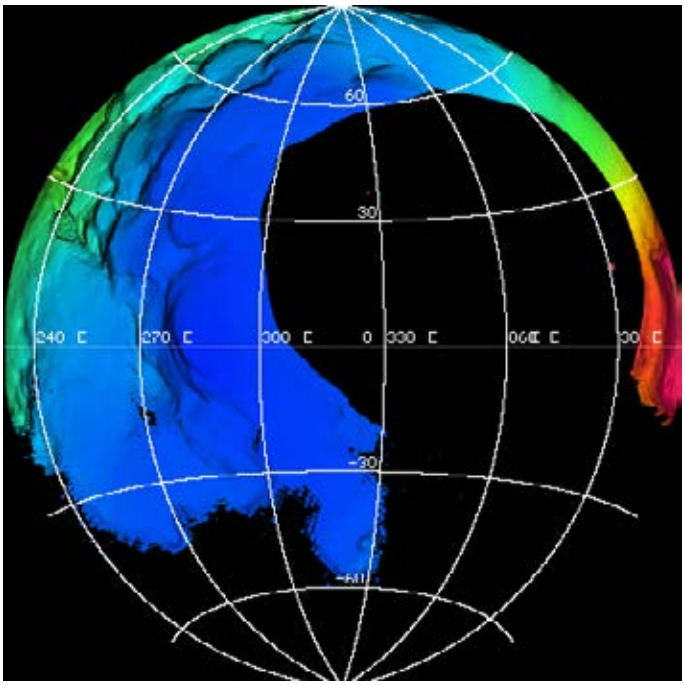
Black areas indicate currently not illuminated unmapped regions on C-G's southern hemisphere, as well as cut regions to adjacent sub-lobes (e.g. at left and right side in 67P_BL_1500_E_0_140).



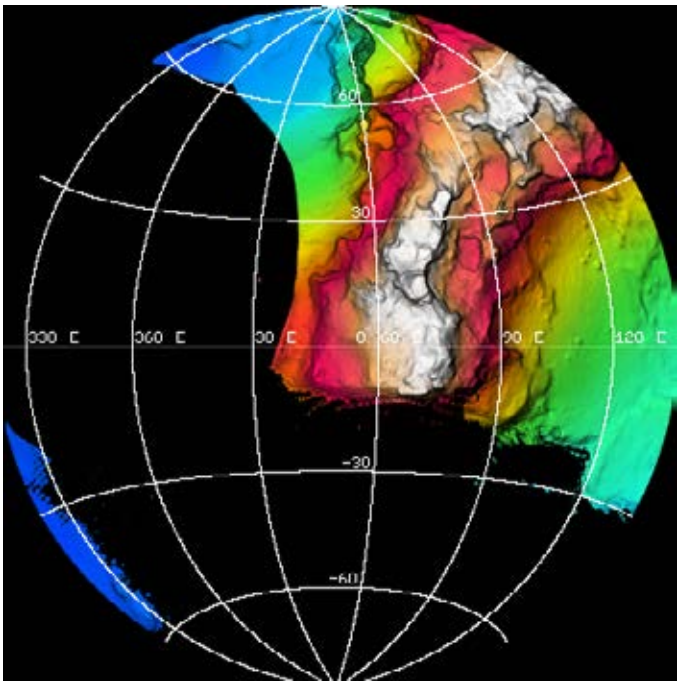
67P_BL_1500_L_0_140



67P_BL_1500_L_0_230



67P_BL_1500_L_0_320

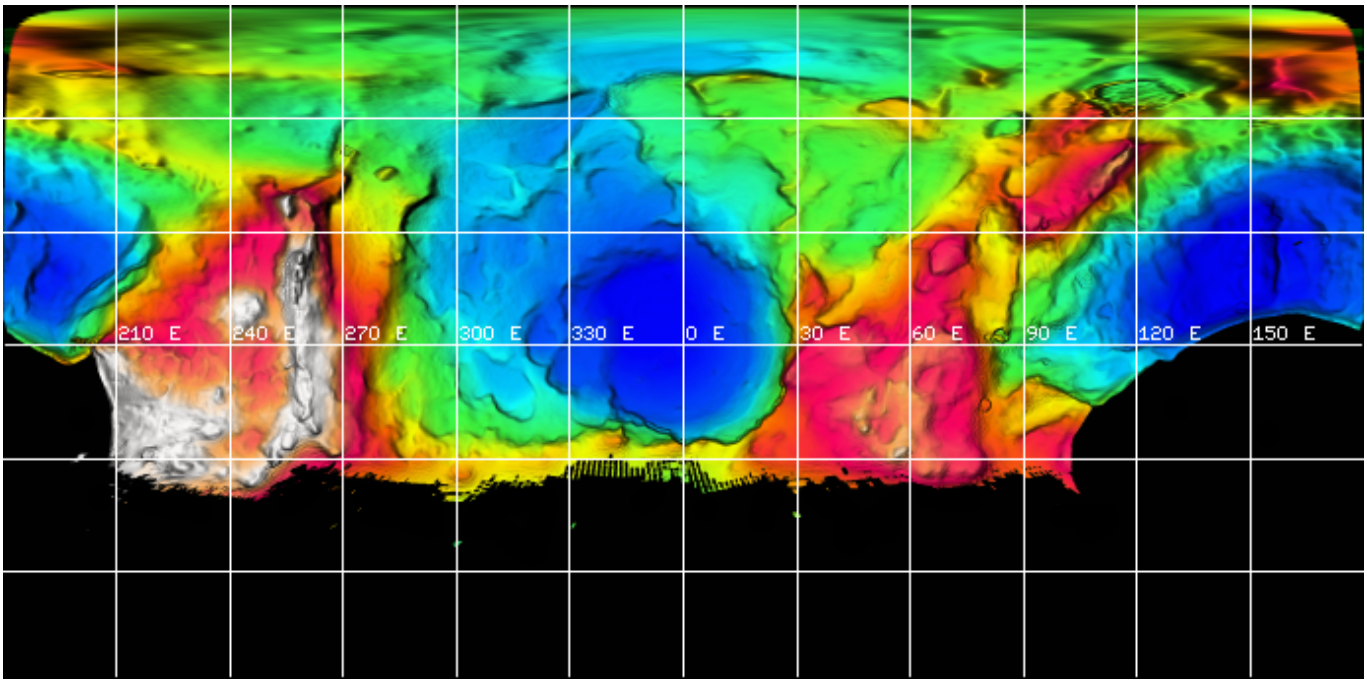


67P_BL_1500_L_0_50

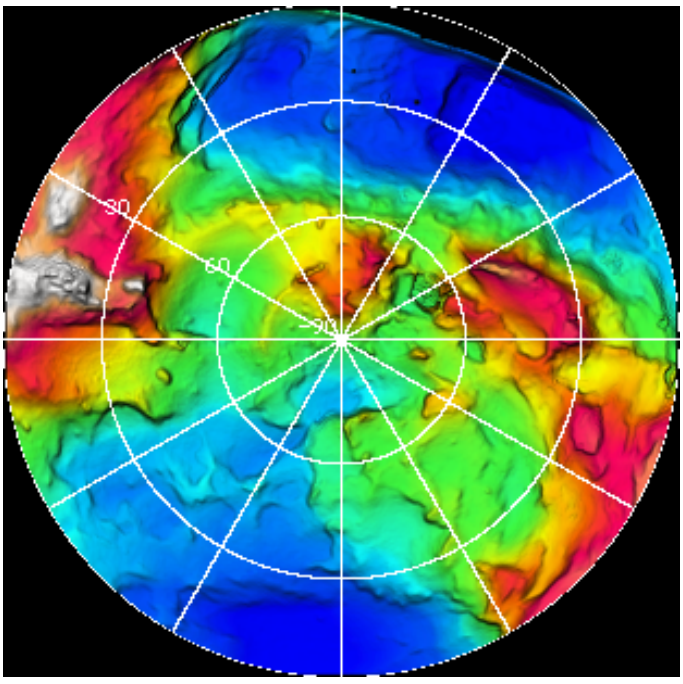
7 standard maps for SL (small lobe)

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

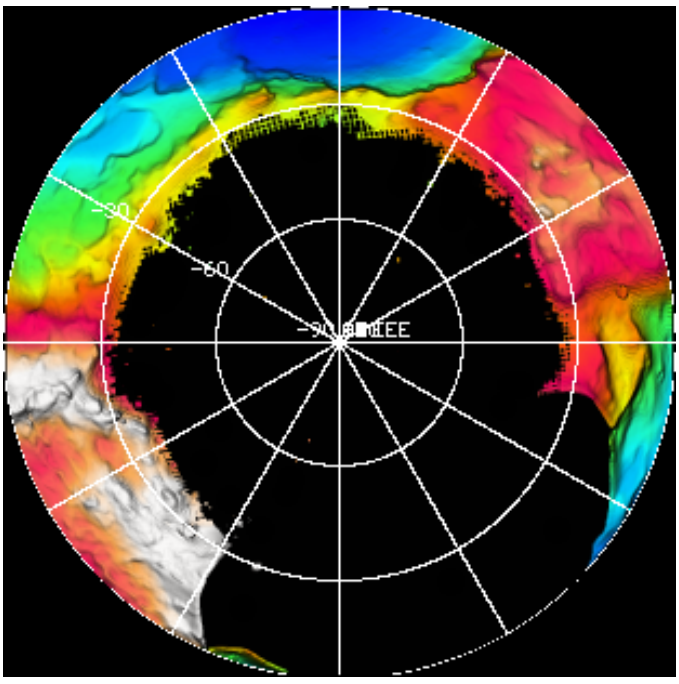
color coding of heights above the 1,100 m reference sphere: blue = -300 m to red/white = 300 m)



67P_SL_1100_E_0_0

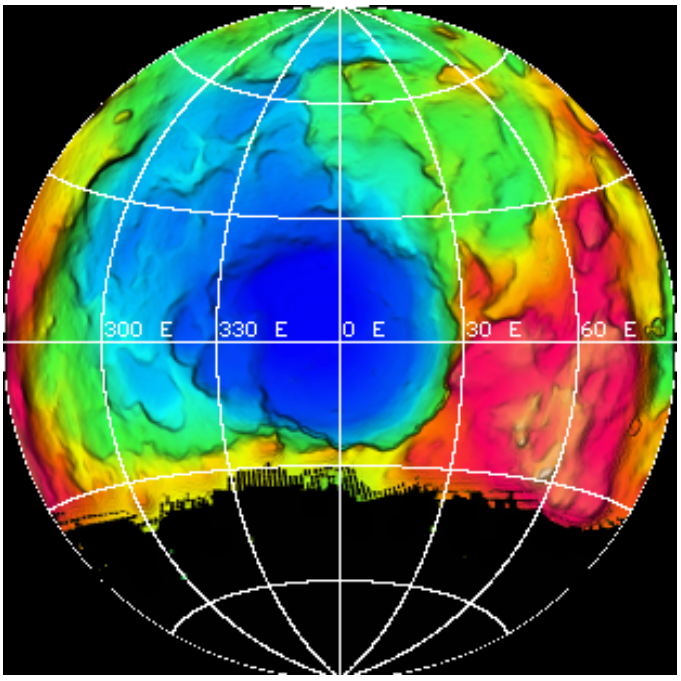


67P_SL_1100_L_90_0

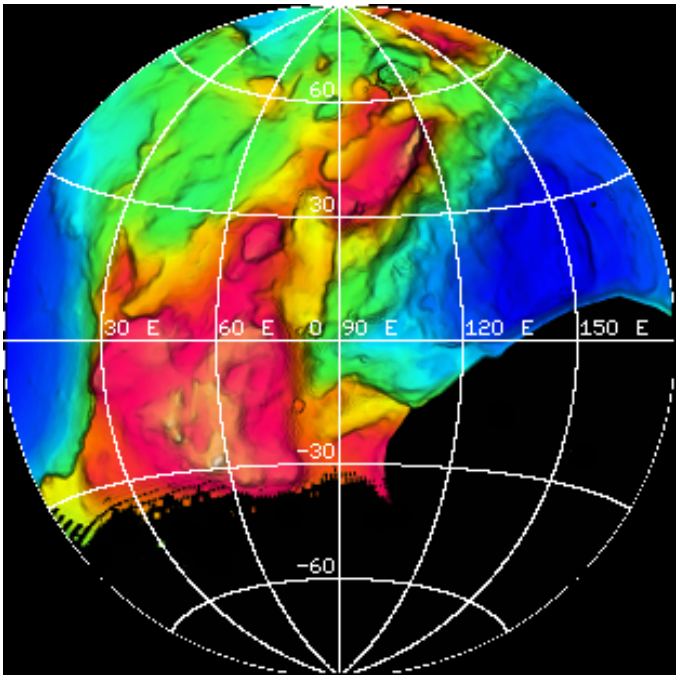


67P_SL_1100_L_-90_0

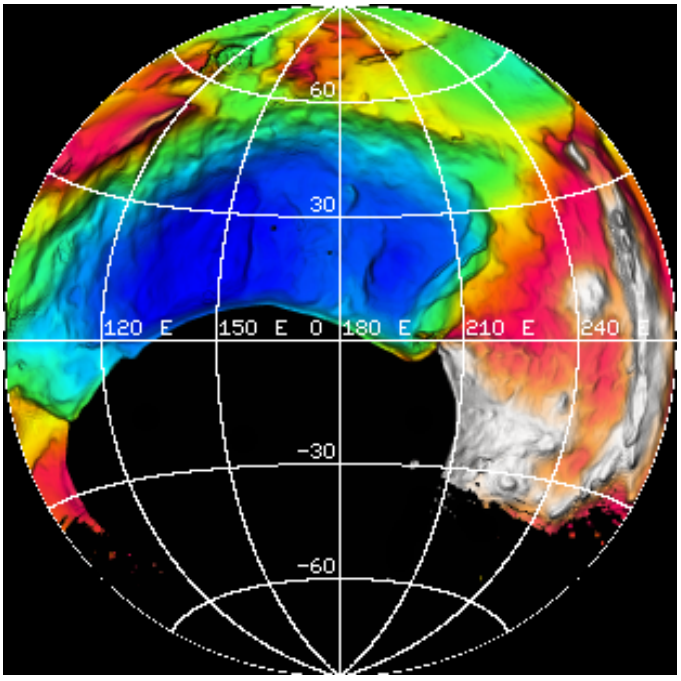
Black areas indicate currently not illuminated unmapped regions on C-G's southern hemisphere, as well as cut regions to adjacent sub-lobes (e.g. at left and right side in 67P_SL_1100_E_0_0).



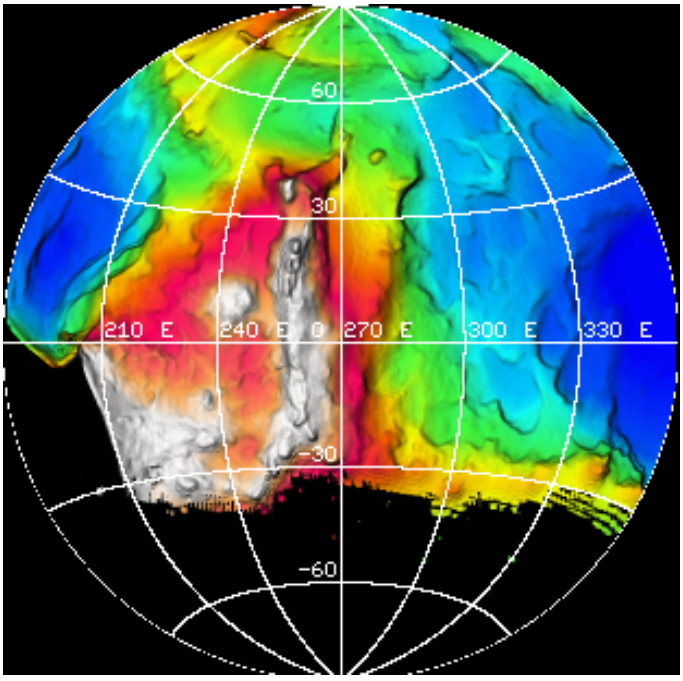
67P_SL_1100_L_0_0



67P_SL_1100_L_0_90



67P_SL_1100_L_0_180

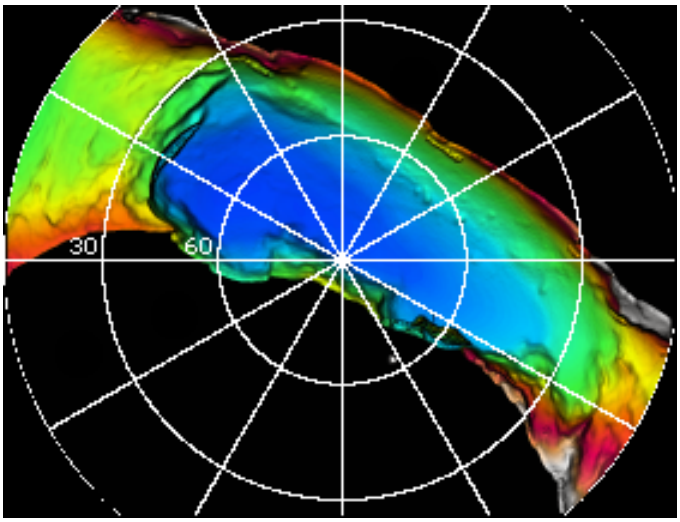


67P_SL_1100_L_0_270

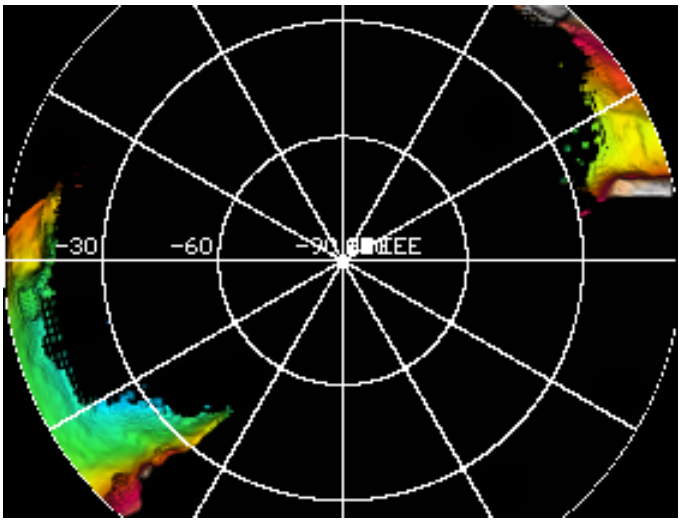
4 standard maps for NR (neck region)

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

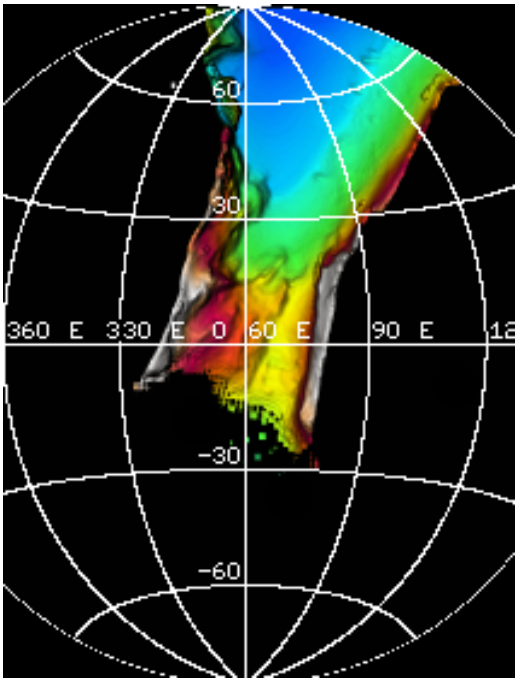
color coding of heights above the 1,000 m reference sphere: blue = -400 m to red/white = 400 m)



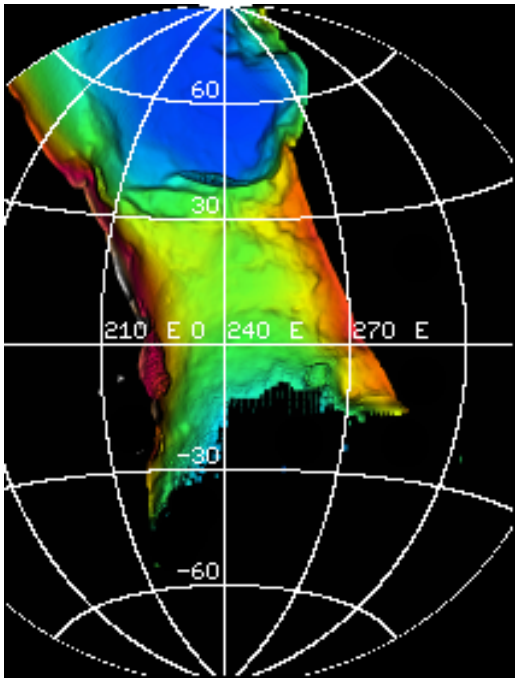
67P_NR_1000_L_90_0



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 C-G'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).