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The global meter-level shape model of comet 67P/Churyumov-Gerasimenko

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ABSTRACT

We performed a stereo-photogrammetric (SPG) analysis of more than 1500 Rosetta/OSIRIS NAC images of comet 67P/Churyumov-Gerasimenko (67P). The images with pixel scales in the range 0.2–3.0 m/pixel were acquired between August 2014 and February 2016. We finally derived a global high-resolution 3D description of 67P’s surface, the SPG SHAP7 shape model. It consists of about 44 million facets (1–1.5 m horizontal sampling) and a typical vertical accuracy at the decimeter scale. Although some images were taken after perihelion, the SPG SHAP7 shape model can be considered a pre-perihelion description and replaces the previous SPG SHAP4S shape model. From the new shape model, some measures for 67P with very low 3D uncertainties can be retrieved: 18.56 km \(\pm\) 0.02 km\(^3\) for the volume and 537.8 kg/m\(^3\) \(\pm\) 0.7 kg/m\(^3\) for the mean density assuming a mass value of 9.902 \times 10\(^{15}\) kg.

Key words. methods: data analysis – techniques: image processing – comets: individual: 67P/Churyumov-Gerasimenko – planets and satellites: surfaces

1. Introduction

For the precise mapping of a planetary body, and for other detailed analyses within various scientific investigations, a 3D shape model at the highest possible level of detail, accuracy, and completeness is a fundamental prerequisite. This is particularly important if the observed body is as irregular and bilobed as the nucleus of 67P, therefore widely interpolated in southern regions. Jorda et al. (2016) applied another technique, the stereo-photoclinometric method (SPC) to more than 5500 OSIRIS NAC images (acquired through June 2015). Additional information from scans of the MIRO microwave instrument on board Rosetta were included in order to further constrain the topography of the southern hemisphere. The result, the SPC SHAP5 shape model (dataset name CG-SPC-SHAP5-V1.1) of 67P, benefits from its better coverage in the southern hemisphere, but compared to the SPG SHAP4S shape model it is evidently limited in its level of detail and its accuracy on the local and regional scale (see Fig. 1). For precise studies of 67P, it is essential to have a detailed 3D model of the entire surface. We decided to extend the 3D coverage of 67P to its southern hemisphere with the same level of

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\(^1\) http://europlanet.dlr.de/Rosetta
5 August 2014 and lasts until 24 May 2015. It includes OSIRIS
images that were already used for the SPG SHAP4S shape model and additional sequences dedicated to 3D shape re-
construction. Several images from other OSIRIS mapping se-
dences during this time period complement the entire used
OSIRIS NAC selection for a total of 1198 images. The subso-
lar latitude at the end of May 2015 is close to the equator, at
about 6°S. For this reason, and because of 67P’s very irregular
shape, there are still some areas at high southern latitudes
that suffer from typically low Sun elevation, and results in slightly in-
creased point spacing in the final shape model at about 10% of
the entire surface of 67P. Other southern summer pre-perihelion
periods, e.g., in July 2015, with image scales only slightly higher
than 3 m/pixel suffer from observational conditions that are not
suitable for our analysis. For operational reasons (to guarantee
the mission safety), the orbit of the Rosetta spacecraft was al-
most perpendicular to the Sun-comet direction so that images
taken at that time suffer from high phase angles (up to 90°).
This orbit strategy was followed over almost the entire Rosetta
mission with few exceptions and is generally a limiting factor to the
availability of adequate image content for many scientific ap-
lications. Appropriate OSIRIS NAC images at scales of 0.8 to
1.4 m/pixel and with sufficient illumination (phase angles \(\ll 90°\)
and subsolar latitudes in the south) were acquired in the first
weeks of 2016. After this period, the phase angle again begins to
rapidly increase to 90°. For a full global coverage, we decided
to include 309 OSIRIS NAC images from this post-perihelion
period. Finally, we filled a very small remaining gap in 67P’s
southern neck region with 24 images that were taken in October
and November 2015. Table 1 summarizes information about the
selected 1531 OSIRIS NAC images for the subsequent SPG pro-
cessing (image times are marked in green in Fig. 2). We only se-
lected images that were acquired with the OSIRIS NAC orange
filter F22 (central wavelength: 649.2 nm, bandwidth: 84.5 nm)
because of its high signal-to-noise ratio (Keller et al. 2007).

### 2. OSIRIS NAC image selection

The previous SPG SHAP4S shape model covers about 70 per-
cent of the surface of 67P, i.e., the entire northern hemisphere and
moderate southern latitudes. For the successful extension of the
existing SPG shape model towards a real complete model we
need an adequate set of additional OSIRIS images that cover
higher southern latitudes. However, if we consider the very short
time period previously used (5 August–3 September 2014), there
may also be additional observations that allow improvements in
already covered regions. The observation and illumination con-
ditions during the Rosetta mission at 67P vary strongly over
time. Figure 2 displays some of the key parameters that help
to select adequate mission and observation phases for the fi-
nal image data subset. Ideally, the desired shape model should
be highly resolved and complete in terms of coverage. There-
fore, and similarly to the SPG SHAP4S shape model, we de-
cided to select 3 m/pixel as an upper limit for the image scale
and to use high-resolution OSIRIS NAC images only. Follow-
ing these criteria, the period that we initially selected starts on
5 August 2014 and lasts until 24 May 2015. It includes OSIRIS

![Fig. 2. Timeline of observation and illumination conditions during the Rosetta mission at 67P. Subsolar latitude (in blue), distance of the Rosetta s/c to the surface of 67P and corresponding OSIRIS NAC image scale (both in red), key dates (in black).](image)

3. Stereo-photogrammetric processing towards the SPG SHAP7 shape model

The previously described dataset of more than 1500 OSIRIS
NAC images constitutes the input for the subsequent stereo-
photogrammetric processing. The latest images are from the
OSIRIS SHAP7 image sequence, thus the new shape model is
called SPG SHAP7. The major aspects of the SPG procedure are
1) the selection of sets of stereo images (stereo models) within

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the observation periods and a set of connecting stereo models between the periods, 2) the stereo image matching within and between these models, and 3) the overall stereo-photogrammetric block adjustment for the derivation of adjusted orientation data (orbit position and pointing) for each image, considering the body’s rotational state. The 3D object point and 3D mesh generation are described in Sect. 4.

3.1. Setup of stereo models

Compared to the SPG SHAP4S model (derived from less than 300 images acquired within a month), the major difference of the input data for the SPG SHAP7 shape model is its size and diversity (more than 1500 images that were taken over more than 18 months). Within each single observation period, we defined stereo models for each image, i.e., combinations of the respective image and of at least two stereo partners that fulfill the typical observation and illumination requirements. We defined additional stereo models that serve as connectors between the single groups of stereo models within each observation period. In total, we defined a block of more than 4100 connected stereo models for the entire SPG SHAP7 shape model.

3.2. Stereo image matching

For each of the defined stereo models, we use SPG’s area-based image matching technique (Wewel 1996) to derive image coordinates of identical points with the images. First, image matching is done in a more sparse way for the generation of a reduced set of tie-points that serves as input for the subsequent stereo-photogrammetric block adjustment. Later on, for the derivation of points for the 3D model itself, this grid is typically as dense as the original pixel size of the respective images. The reduced set of tie-points for the block adjustment comprises more than 20,000 points. The total number of points for the final SPG SHAP7 shape generation is about 6 billion.

3.3. Improvement of orientation data by means of stereo-photogrammetric block adjustment

Based on the reduced set of tie-points, we used a stereo-photogrammetric block adjustment that consists of a least-squares adjustment of observations (image coordinates of the tie-points) within (multi-)stereo images (i.e., the stereo models), in order to determine improved orientation data (spacecraft position and attitude) in the body-fixed coordinate frame from the initial set of orientation data. The typical initial or a priori set of orientation data consists of SPICE kernels (Acton 1996) and includes nominal SPICE SP orbit kernels, defined in the J2000 reference frame, for 67P and for the Rosetta spacecraft position, as well as nominal SPICE C kernels about the spacecraft attitude (pointing). The orientation of the body-fixed coordinate frame in the J2000 frame (i.e., the rotation model) is typically described by a SPICE PC kernel that describes planetary constants, e.g., the body’s pole orientation, a possible precession, and the rotation period. For a pre-perihelion period from August to early September 2014, we detected a precession-like complex rotation for 67P which is described in a SPICE PC kernel (Preusker et al. 2015). This kernel also defines 67P’s “Cheops” reference frame. The effect of the precession amounts to about ±3 m on 67P’s surface. Later, the presence of this precession was confirmed by Gutiérrez et al. (2016) and Jorda et al. (2016). Additionally, a significant change from a constant to a varying rotation period, starting in late 2014 and caused by effects from sublimation activity, had been predicted early in the mission by Keller et al. (2015) based on the SPG SHAP4S shape model. This change in the rotation period of 67P was confirmed later within different analyses of image data that were taken around the comet’s perihelion (e.g., Jorda et al. 2016). SPICE C kernels that describe this varying rotation of 67P’s body-fixed frame in the J2000 frame are included in ESA’s set of relevant Rosetta kernels. These kernels define the state and orientation of the coordinate frames of 67P, of the Rosetta spacecraft, and of the instruments on board Rosetta over the entire mission. These kernels were used (with one exception) for the transformation of initial values for the orientation data to the coordinate frame of the SPG SHAP7 block adjustment, 67P’s body-fixed frame 67P/C-G.CK. The exception is represented by the set of already existing adjusted orientation data for OSIRIS NAC images of the previous SPG SHAP4S processing. Since it considered the comet’s pre-perihelion precession, we used orientation results from this previous adjustment as initial values within the SPG SHAP7 block adjustment, widely minimizing the possible influence of a systematic effect (the SPICE C kernels for 67P unfortunately do not contain the previously mentioned precession).

4. Final SPG SHAP7 shape model

Based on the adjusted orientation data and considering the image distortion model, we computed a 3D forward ray intersection for 6 billion matched points coordinates. The result is a set of 3D points in the body-fixed Cheops reference frame 67P/C-G.CK. Because of the redundancy from an intersection of three or more rays, we estimated additionally the intersection accuracy of each point. Secondly, we eliminated points that were derived from less than three stereo partners. We also eliminated outliers, i.e., points with a 3D intersection error that is larger than three times the mean intersection error within the respective stereo model. The remaining 3.4 billion points provide a mean 3D intersection accuracy of 0.3 m, which is representative of the mean accuracy of the final shape model. These points were then filtered by averaging points that fell within voxels of 1 m in size. We finally derived a meshed dataset using the Poisson surface reconstruction functionality in version 1.3.3 of the mesh processing system MeshLab© (Cignoni et al. 2008). Henceforth, we adopt the “vertex” for a 3D point and “facet” for a triangular mesh of three vertices. The final meshed SPG SHAP7 shape model consists.

\[ ftp://ssols01.esac.esa.int/pub/data/SPICE/ROSETTA/kernels/nk \]
of 22 million vertices and 44 million facets. The technical name for this version of the SPG SHAP7 shape model is CG-DLR_SPG-SHAP7-V1.0. Figure 3 shows six different views of the new model. Details about the SPG SHAP7 shape model and some characteristic key parameters derived from this model are listed in Table 2. For comparison, we added the respective parameters for the SPG SHAP4S model and the SPC SHAP5 model. For the derivation of 67P’s mass, we used the volume of (9.98 ± 3) \times 10^{12} kg from Pätzold et al. (2016). For compatibility within Table 2, we transformed 1σ uncertainties from Jorda et al. (2016) to 3σ estimates and finally reduced the uncertainties for the volume and bulk density measures from Preusker et al. (2015) since their assumed high uncertainty of 67P’s center of mass was not confirmed later. We also derived various representations with a reduced number of facets – more adequate for some scientific applications – by applying the quadratic edge collapse decimation function in MeshLab©. The final dataset is available at the europlanet website1.

5. Summary and outlook

Earlier analyses used OSIRIS NAC data for the derivation of the SPG-based shape model (SPG SHAP4S, Preusker et al. 2015) which provided detailed 3D information for about 70% of the surface of comet 67P, mainly on the northern hemisphere. With integrated additional OSIRIS NAC images from September 2014 to February 2016, we now present the SPG SHAP7 shape model, describing the entire surface of comet 67P with meter-scale lateral spacing and vertical accuracy typically of a few decimeters. We also achieved local improvements in low northern latitudes, based on observation phases in late 2014. Although some post-perihelion stereo images from the SPH7 image sequence from early 2016 have been used to fill small gaps at high southern latitudes, the SPG SHAP7 shape model can be essentially considered a complete description of the pre-perihelion status of the surface of comet 67P’s nucleus. Nevertheless, the image dataset spreads over more than 18 months. Therefore, we recommend that any study of local/regional surface changes along with 67P’s perihelion passage must be performed with care and would probably work better with special subproducts of this global model. We plan to improve our model further, on both a global and local scale, by including results from pending investigations of the rotational state of 67P, particularly of the development of many. The support of the national funding agencies of Germany (DLR), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged. This work has also received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 686709 (MiARD).

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