MiARD

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Deliverable Report

Work Package and Leader	WP1, Frank Preusker (DLR-PF)
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MiARD D1.1

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Summary

The high-resolution reconstruction of solar system bodies is usually done by one of two separate approaches, either *(i)* stereo-photogrammetry (SPG), or *(ii)* stereo-photoclinometry (SPC also known as "shape-from-shading" in the computer vision community). While SPG is a well-established purely geometric approach, SPC is a more recent technique which combines sparse stereo information with local gradient values estimated using pixel-to-pixel intensity variations It is important to mention here that the two approaches are highly complementary (the high geometric accuracy of the SPG approach versus the fine level of detail captured by the SPC method), which is why they can be combined. Taking the SPC approach as a starting point, the MiARD project partner **CNRS** (the Laboratoire d'Astrophysique de Marseille) has developed and tested a new reconstruction method called "MSPCD" (Multi-resolution Stereo PhotoClinometry by Deformation) that combines these approaches to shape reconstruction. Using this new approach within the MiARD project, we describe below the generation of two sets of MSPCD local digital terrain models (hereafter DTMs) which have been combined with different SPG global models (one, SHAP7, reconstructed in the frame of the MiARD project (see also the preliminary version of this report, deliverable D1.8) to create a combined SPG/MSPCD model of the nucleus of comet 67P/Churyumov-Gerasimenko.

Details (scientific and technological achievements)

1 Approaches used to develop the global model

1.1 Generation of local MSPCD digital terrain models

In 2013, **CNRS** started the development of the MSPCD approach, which implemented an SPC method based on a direct non-linear optimization loop using a quasi-Newton large-scale minimization algorithm called "L-BFGS-b"[1]. In MSPCD, a triangular mesh is deformed at each vertex until a set of synthetic images best-reproduces their observed counterparts[2]. The method currently produces models which are a better match (when rendered) to the observed images than previously used methods (e.g., SPC). The method does not implement stereo as such, but it can take into account stereo constraints from an external source (e.g. an SPG model) when available. Here two alternative SPG models of comet 67P, either the SPG SHAP4S[3] or the SPG SHAP7[4] have been used as initial models.

Within the MiARD project, the MSPCD method has been used to produce two families of local digital terrain models (DTMs):

(i) For the deliverable described here (D1.1 "A global DTM constructed by a method combining the stereo and clinometry information") a set of local DTMs (that used the two different initial SPG models mentioned above) at a resolution of 1 m to 2 m having the maximum surface coverage and

(ii) For the deliverable D1.2 "A set of local DTMs" one set of local high-resolution DTMs of areas of interest, at a higher resolution of 3 dm to 10 dm comparable to the resolution of the Rosetta/OSIRIS NAC images used .

For the generation of deliverable D1.1, the local DTMs are generated in three steps. First, a low-resolution (80K facets, 20 m resolution) SPG SHAP4S model is

[1] Morales et al., ACM Trans. Math. Soft. 38, 1, 2011 and references therein

[2] Capanna et al., Vis. Comp. 29, 825, 2013

[3] Preusker et al. "Shape model, reference system definition, and cartographic mapping standards for comet 67P/Churyumov-Gerasimenko – Stereo-photogrammetric analysis of Rosetta/OSIRIS image data" (2015) Astronomy & Astrophysics vol 583

[4] F. Preusker, F. Scholten, K.-D. Matz, T. Roatsch, S. Hviid, S. Mottola, J. Knollenberg, E. Kuehrt, Osiris team, The global meter-level shape model of comet 67p/Churyumov-Gerasimenko, submitted to A&A (2017).

segmented into 100 “maplets”[5]. An overlap region between the maplets is kept to facilitate their fusion into a combined global model. Second, a set of OSIRIS/NAC images showing the corresponding region of the comet acquired under different viewing and illumination angles is selected. Third, each maplet is optimized separately with the MSPCD method up to a resolution of about 1.5 to 2 m. At the end of the optimization, each maplet is visually inspected to look for possible artefacts resulting from the optimization and its final chi-square value is recorded. A “quality map” is also generated from the averaged residuals between the calibrated pixel values of the observed and the synthetic images. The typical computational time is 3-5 days for one maplet. Therefore, **CNRS** use a local cluster of computers with 420 cores to perform the calculations in parallel. Figure 1 shows maplet number 55 before and after optimization as well as the quality map. Additionally, a comparison of observed images used to reconstruct this maplet with the corresponding synthetic images is shown in Figure 2. In the latter, one can notice significant differences between the observed and synthetic images (e.g., for images #1 and #4 in Figure 1). They reflect the difficulty of reconstructing such sharp terrains with clinometric methods. Note that these differences are automatically reflected in the quality map associated to the maplet (Figure 1c).

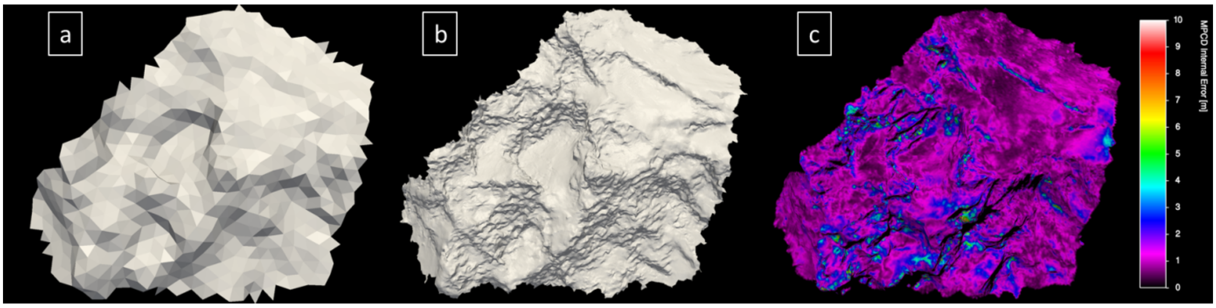

Figure 1. Example of a maplet from first set of maplets (here maplet number 55): (a) show the starting maplet at a resolution of 20 m (level of resolution one), (b) the final optimized MSPCD maplet at a resolution of 1.6 m (level of resolution five) and (c) the maplet error map (bottom).

1.2 Combination of the SPG global model and MSPCD maplets

CNRS combined the MSPCD maplets with the SPG global model delivered by **DLR-PF** as reported earlier in deliverable D1.8. This combination is achieved in two steps. First, each maplet is geometrically aligned with the SPG global model. Second, the aligned maplets are merged into the global model.
The first step (see Figure 3) is performed by deformation of the MSPCD maplets towards a decimated version of the SPG model containing 500K facets

[5] A “maplet” is a local DTM resulting from the segmentation of the global DTM.

(corresponding to a sampling of about 10 m). The accuracy of this operation has been estimated to be about 0.5 m to 1 m (rms). The deformation is achieved by moving each vertex of the MSPCD model along its local normal vector towards the surface of the SPG model. The second step is more complex and involves two operations:

a) the overlap regions of neighbour maplets are accurately re-aligned to prevent any discontinuity of the surface and of its slope (see Figure 4), and
b) the maplets are bi-linearly interpolated on the sampling grid of three SPG models of 12M, 20M and 44M facets. This operation leaves the SPG model unchanged at locations of the surface where no MSPCD maplets are available.

The outputs are thus models which closely follow (at a scale of 10 m) the topography of the SPG model, enhanced with topographic details (at a scale of about 3 m to 4 m).

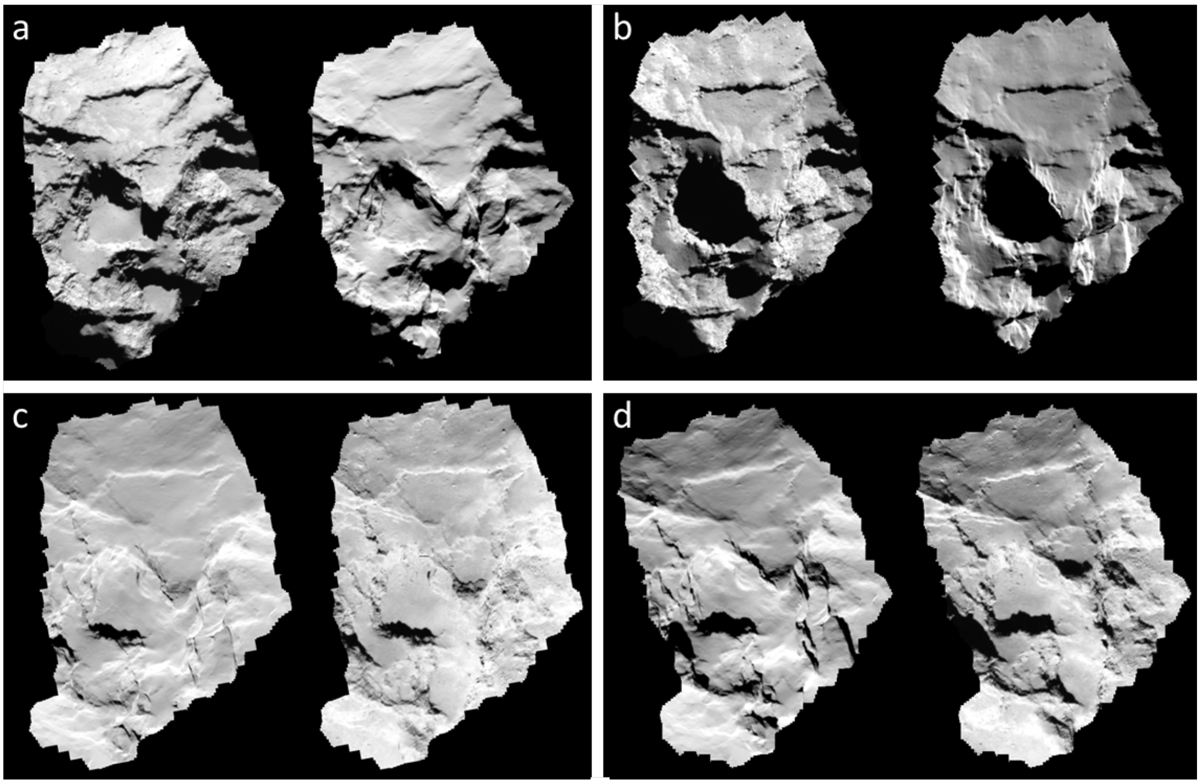

Figure 2. Sample of 4 images (with different viewing and illumination conditions) out of 14 images used to reconstruct the maplet number 55 (see Figure 1). In each panel, the left image is a sub-frame of an observed OSIRIS/NAC image and the right image is the corresponding synthetic image generated with the maplet.

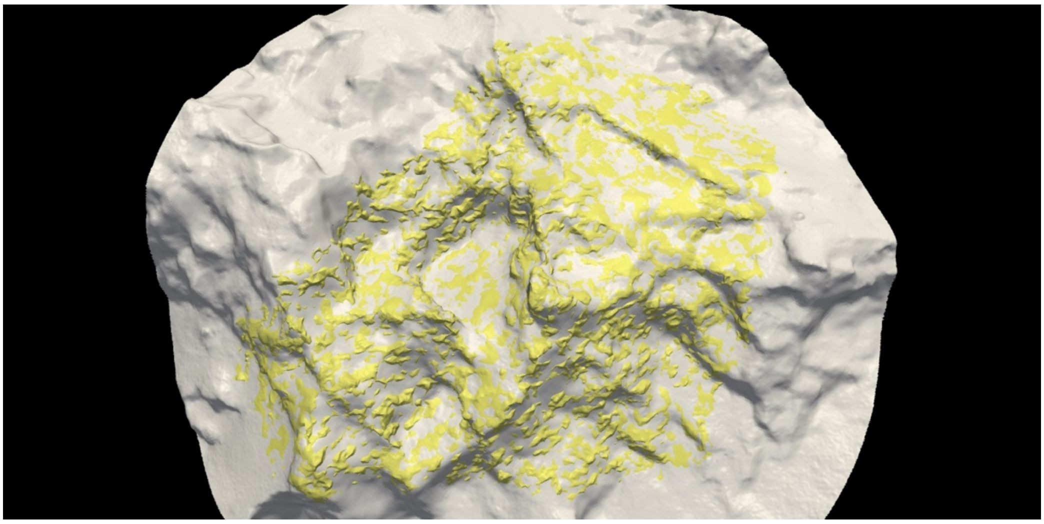

Figure 3. Extract of the SPG SHAP7 model (deliverable D1.8) in grey together with maplet number 55 of maplet set 1 in yellow. This image illustrates the accuracy of the alignment of MSPCD maplets with the SPG model.

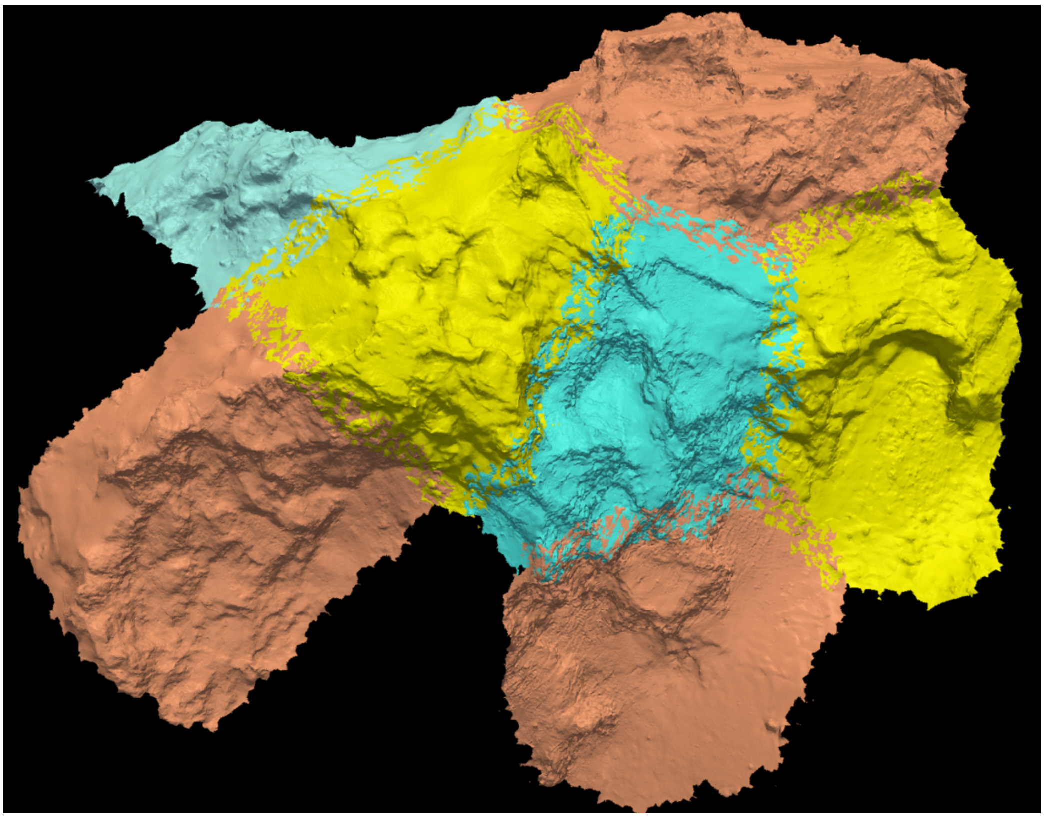

Figure 4. Group of overlapping maplets around maplet number 55 after accurate re-alignment of the overlapping regions between two neighbour maplets. Each colour represents a maplet and interlaced colours indicate overlapping regions.

2 Current status

2.1 Generation of two sets of local MSPCD digital terrain models

Two subsets of 90 maplets (first subset) and 100 maplets (second subset), corresponding to two different segmentations of the initial 80K shape model have been optimized. For the first subset of maplets, the starting model used was the so-called "SHAP4S" model generated prior to the deliverable D1.8 SPG model, which did not include all of the southern hemisphere of the comet. (This was done in order to speed up the work. It is not thought that the choice of starting model has any significant influence on the final product, and all maplets were eventually combined with the SHAP7 model from the project). Three levels of resolution have been used in order to reach the final sampling of 1.5 m to 2m on the final maplets. For the second subset of 100 maplets, a full coverage global model (SPG "SHAP7" model, as described and delivered with the earlier deliverable D1.8 "A preliminary global DTM reconstructed by a method combining the stereo and clinometry information") has been segmented. A slightly different optimization strategy was adopted for the second subset: (a) the pointing of the camera has been fine-tuned iteratively with the topography in the optimization process, and (b) two optimizations with 3 and 4 levels of resolutions have been performed for each maplet. The final maplet with the lowest chi-square was selected. When using four levels of resolution, the starting maplet was decimated to the level of resolution just below using the "ReMesh" algorithm[6] in order to achieve a uniform sampling at the same final resolution of 1.5 to 2 m.

Table 1 Summary of parameters for the two sets of MSPCD maplets.

	Maplet set #1	**Maplet set #2**
Number	56	47
Minimum sampling	1.54 m	1.96 m
Maximum sampling	1.84 m	2.34 m
Averaged surface	0.775 km²	0.930 km²
Total surface	43.4 km²	43.7 km²
Time range of images: - Begin - End	06-AUG-2014 16-JUN-2016	06-AUG-2014 14-APR-2016
Total number of vertices	15.9 M facets	9.4 M facets

[6] (Attene and Falcidieno, In Proceedings of Shape Modeling International SMI'06, IEEE C.S. Press, pp. 271-276, 2006)

Status of maplet subset 1

Only 56 maplets were selected for use, 44 maplets were rejected for the following reasons:

- 10 maplets due to an insufficient number of images of the corresponding areas found by our image selection software,
- 3 maplets due to numerical problems during the optimization,
- 11 maplets due to broad linear artefacts, and
- 20 maplets due to unacceptable residuals (chi-square above 5000) and/or bad matching of the observed images.

Status of maplet subset 2

Only 47 maplets were selected, 43 maplets being rejected for the following reasons:

- 14 maplets due to an insufficient number of images of the corresponding areas,
- 5 maplets due to numerical problems during the optimization,
- 5 maplets due to broad linear artefacts, and
- 19 maplets due to unacceptable residuals (chi-square above 5000) and bad matching of the observed images.

Coverage maps of the two sets of maplets are shown in Figure 5. The coverage map of the combination of maplets (union of the two subsets of selected maplets) is shown in Figure 6. The final surface covered by the two combined sets of MSPCD maplets is 40 km^2 (85 percent of the total surface of the comet).

The rejection of many maplets is due to several problems:

a) insufficient range of incidence and emission angle coverage of the available images,
b) initial slopes too far from the target solution (in the case of maplet set 1 using SHAP4S in the southern hemisphere), and
c) in a few cases incorrect manual selection of images.

CNRS emphasizes the fact that comet 67P has an extremely challenging topography for a reconstruction by photoclinometry techniques due to both its extremely rough surface in a lot of areas and its bilobate structure which limits the acquisition of images under different illuminations and/or viewing angles in some regions like the neck.

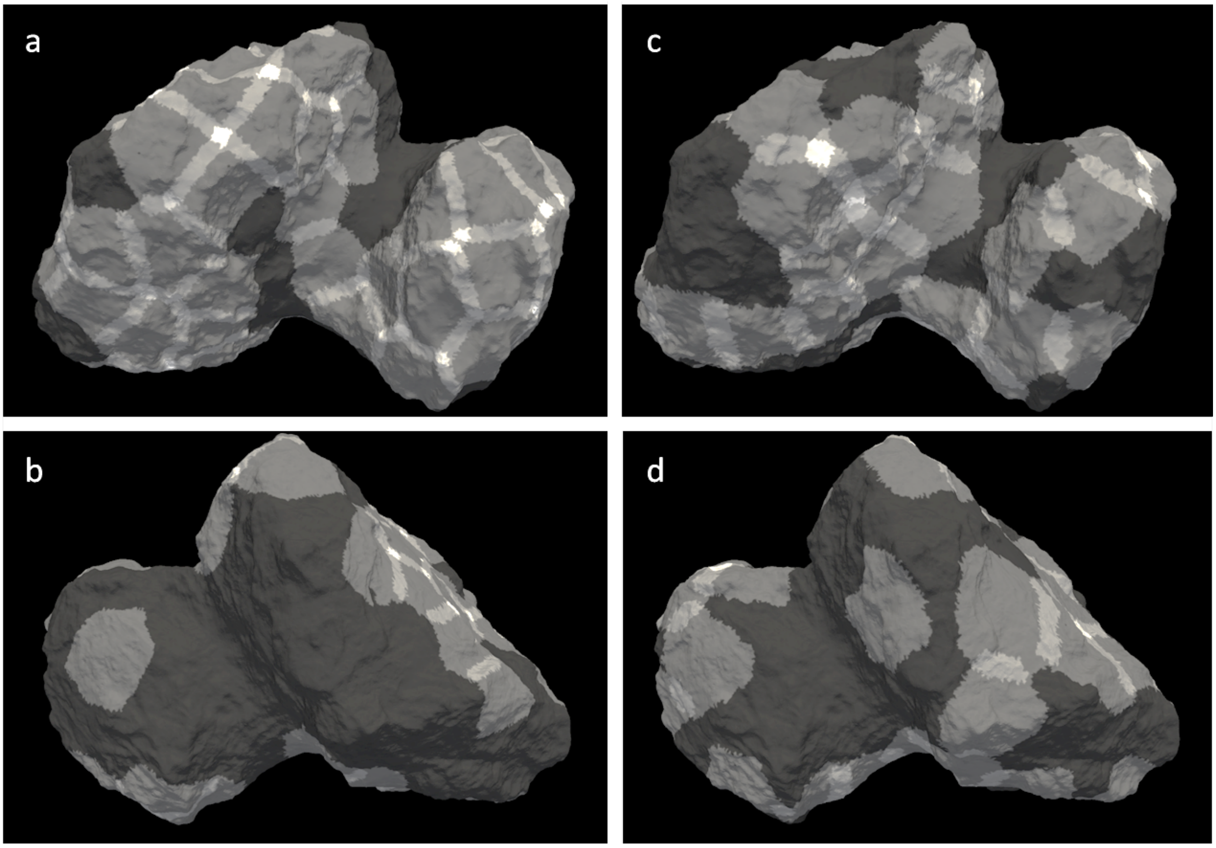

Figure 5. Coverage maps of maplet set 1 (a,b) and maplet set 2 (c,d). The panels show views from the northern (a,c) and southern (b,d) poles. The models are projected onto a decimated version of the SPG SHAP7 model.

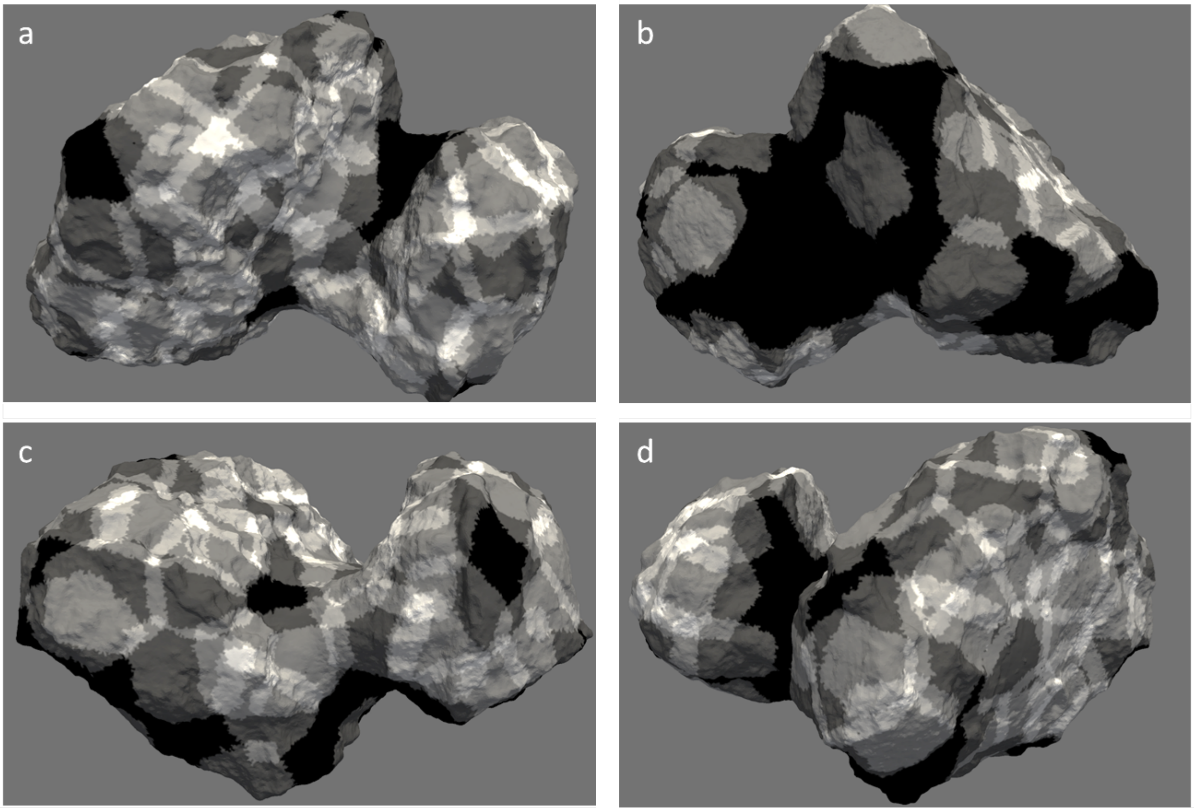

Figure 6. Combined coverage maps of the two sets of maplets used to generate the global combined SPG/MSPCD model. Upper row shows the North (a) and South (b) views, whereas the lower row shows the Equatorial views from 270 degree East (c) and the 90 degree East (d) directions.

2.2 Generation of the final global stereo-photogrammetry/photoclinometry model

Several versions of the initial SPG SHAP7 model (see deliverable D1.8) have been used by **CNRS** to build the final combined SPG/MSPCD models by interpolation of the two sets of maplets (see section 2.1). Here, SPG models with 12M (2 m sampling), 20M (1.5 m sampling) and 44M facets (1 m sampling) have been used for this purpose. For each sampling, a global model with the raw maplets has been created (see section 2.1). All the models have been delivered in the "Cheops" reference frame (Preusker et al., 2015). Figure 7 shows the combined SPG/MSPCD model with twenty million facets built from the raw maplets. Figure 8 shows details of the SPG/MSPCD model and for comparison the SPG SHAP7 model that was completed earlier in time for the preliminary version of this deliverable (D1.8).

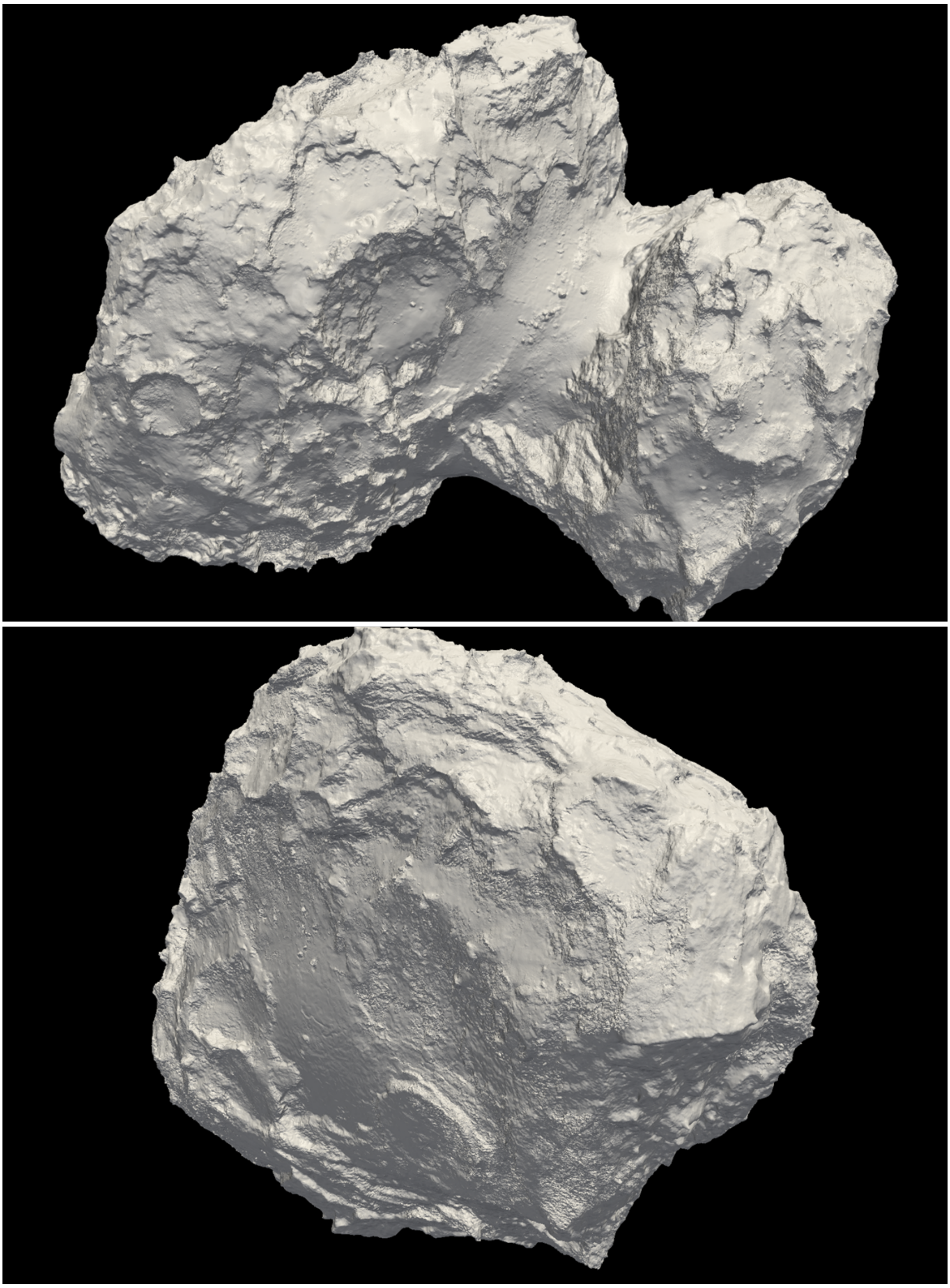

Figure 7. Two views (upper panel from the north pole, bottom panel is an equatorial view from longitude 180°) of the combined SPG/MSPCD model of comet 67P with 20 million facets.

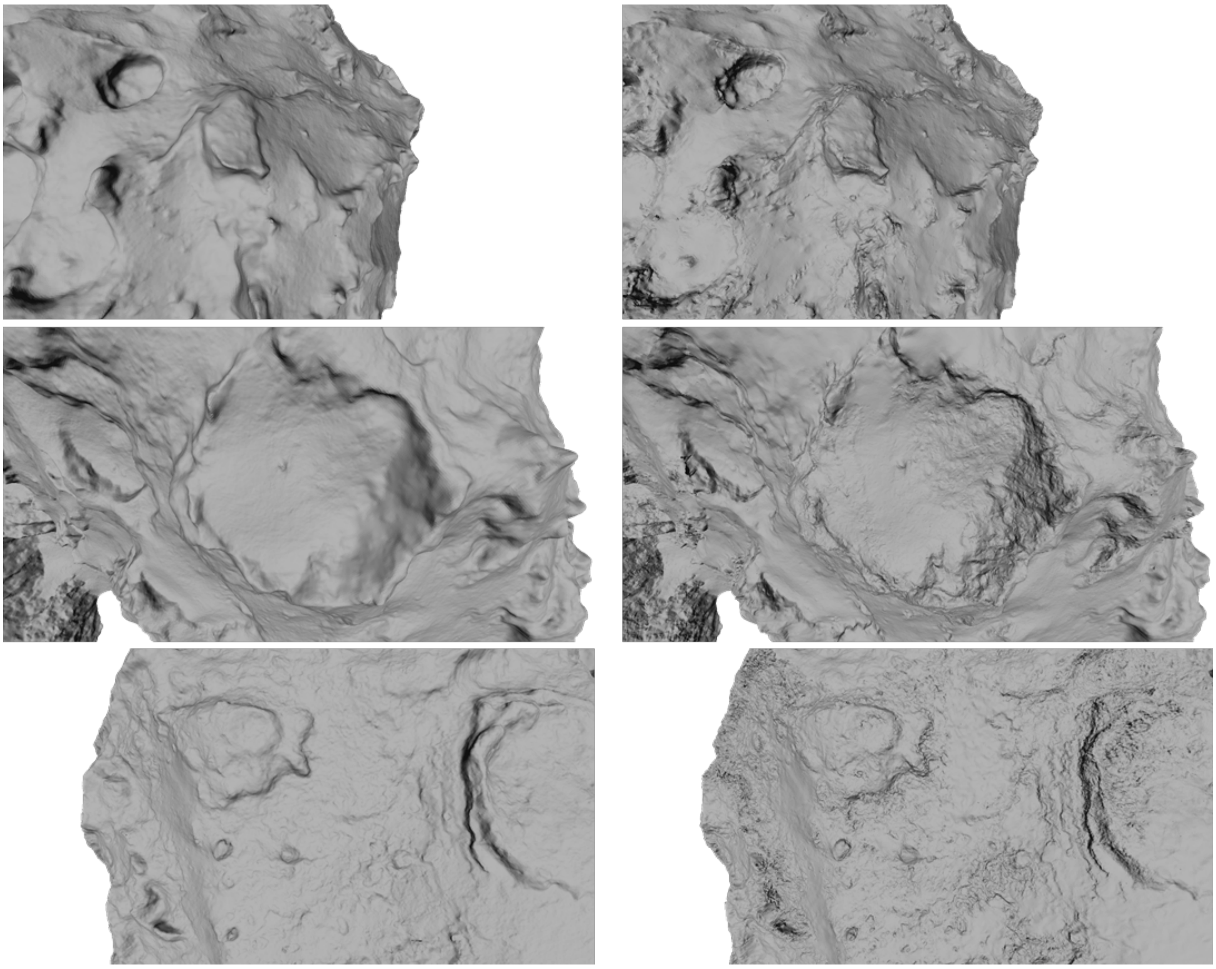

Figure 8. Three zoomed views of the SPG SHAP7 model (left) and 20M facet combined SPG/MSPCD model (right) making clear the extra detail in the latter.

Publication and archiving of the datasets:

The delivery of the D1.1 products will be performed following the usual policy defined by the Rosetta/OSIRIS consortium for shape models (and consistent with the scope of the H2020 call COMPET-5-2015 to which the MiARD project is a response). The delivery will be made in parallel both to the PSA archive of the European Space Agency and to NASA's Planetary Data System (Small Body Node) using version 3 of the PDS format used by both archives. This will ensure the longterm availability and 'findability' of the datasets. The review committee will be organized by the NASA PDS node with ESA members of the Rosetta consortium in it. The datasets will be made available both at PSA and at PDS/SBN (the two archives mirror each other). We propose to perform the final delivery of the D1.1 products after submission and peer review of the associated manuscripts (products D1.5 and D1.6 due to be delivered in M21 (November 2017)) in order to carefully check and prepare the products and associated PDS documentation.

We emphasize that in the frame of the MiARD project we did not budget for the extra effort that would be required for a delivery of PDS v4 products (a format introduced since the MiARD proposal was made). This new format is significantly more complex, and does not yet have good tools to support the archive preparation. We will therefore use the PDS v3.8[7]. The PDS formats define e.g. file formats, compression algorithms, cartographic standards and metadata.

The project will continue to explore ways of making the datasets available to the interested community on a faster timescale without compromising academic standards and traceability, or the 'FAIR' goals of making data findable, accessible, interoperable and reusable. This might be done by using the CERN data system in conjunction with an Astronomy and Astrophysics publication for D1.5 "Manuscript on the final shape of the nucleus, with surface slope and surface gravitation".

3 Description of the D1.1 products

The datasets that make up deliverable D1.1 are available on request from the project, pending acceptance by an appropriate archive as described above.

The deliverable products are separated in two parts.

1) The data/ subdirectory contains the following models:

- the final combined SPG/MSPCD models with 12, 20 and 44 millions of facets ,
- one hundred and three selected local DTMs from the two subsets of maplets (56 maplets in set #1 and 47 maplets in set #2), and
- the combined SPG/MSPCD models built with the individual sets of maplets.

2) In addition to the models, extra information is contained in the extras/ directory:

- the geometric parameters of the maplets (number of facets, centre, surface, and averaged sampling),
- maplet coverage models,
- views of the coverage maps of the maplets,
- views of the global models, and
- rendered images of the global models corresponding to images observed by the OSIRIS/NAC camera.

All models have been made available in the binary polygon file format (PLY) and all images as portable network graphic (PNG) files.

[7] See https://pds.jpl.nasa.gov/tools/standards-reference.shtml

Deviations from the DoA

None.

Conclusions, expected impact and use of deliverable, outlook

Conclusions

This final report describes the generation of the final combined SPG/MSPCD global digital terrain model of comet 67P (product D1.1). The delivery also includes the local DTMs used to build this model. For ease of use, the model has been delivered with three samplings: 2 m (12M facets), about 1.5 m (20M facets) and 1 m (44M facets).

The final version of the datasets for deliverable D1.1 (and D1.2) will be used e.g. to measure the local erosion due to the outgassing of the comet. Thus deliverable D1.7 " Manuscript on observed erosion depths" will be generated using the global DTM described here. For other purposes in MiARD (e.g. the modelling of outgassing) which do not benefit from such a high level of detail, the SPG SHAP7 global shape model has been used (for details, see the earlier D1.8 delivery report).

Impact

In addition to the anticipated information on erosion rates as a result of the perihelion passage of comet 67P (deliverable D1.7), we expect that the new very high-resolution SPG/MSPCD combined model will have a significant impact beyond the MiARD project consortium in the wider planetary science community as it will improve several applications, including:

(i) a detailed geomorphological analysis of the cometary surface for areas of scientific interest,

(ii) a finer analysis of the reflectance/roughness properties based on a more accurate small-scale knowledge of the slopes, and

(iii) a more thorough analysis of the Rosetta/Philae landing site(s).

We also expect the now-proven technique to find application to datasets from future missions to other solar system bodies.

GLOSSARY

DTM	Digital Terrain Model
MSPCD	Multi-resolution Stereo PhotoClinometry by Deformation
rms	root mean square
PLY	Polygon File Format
PNG	Portable Network Graphics. A lossless ompressed raster image format
SPC	Stereophotoclinometry
SPG	Stereophotogrammetry