OPTICAL MEASUREMENTS FOR ROSETTA NAVIGATION NEAR THE COMET

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Abstract: *In July 2014, the ESA interplanetary spacecraft (S/C) Rosetta became the first mission to rendezvous with a comet (67P/ Churyumov-Gerasimenko). The S/C drew near enough to the comet to take high resolution images of the nucleus with the navigation cameras. Optical measurements were used near the comet to navigate the S/C during the approach, mapping and characterization, landing and escort phases. The cometary phase was complex and diverse, forcing various scenarios to be envisaged: hyperbolic arcs in a pyramidal shape from 100 km down to 50 km distance, circular orbits from 30 km to 10 km and several close flybys. Throughout these varied trajectories pixel positions of landmark observations were determined automatically on-ground using the maplet technique. This paper presents the algorithms, rationale and relevant results that validate the optical navigation philosophy carried out at ESOC.*

Keywords: *Optical navigation, landmark tracking, maplet, shape reconstruction.*

1. Introduction

On May 2014, Rosetta entered the comet phase of its mission. It approached the comet 67/P Churyumov-Gerasimenko, characterised it, deployed the lander and orbited around the comet collecting scientific observations. The operations were split in the following phases: Comet approach, Comet characterisation, Comet global mapping, Close observation, Lander delivery and Extended monitoring.

During the approach phase the main objective was to detect the comet and to navigate towards it, while reducing the relative S/C-comet relative velocity. Comet features were not yet resolved on the images therefore only comet centre observations were made. Far approach optical observations are explained in detail in ref[1]. However, this paper focuses on the optical measurements of surface landmarks near the comet nucleus.

The initial characterisation phase started on August 7th 2014 at a distance from the comet (ca. < 130 km), when it was first possible to obtain full images of the comet with the navigation cameras (NAVCAM). Since then, and through out the rest of the mission phases, Rosetta navigated relying on landmark observations which were obtained on-ground by processing NAVCAM images.

Although the very first landmark observations were obtained visually with the help of a GUI (ref [8]), after a few weeks of operations, feature detection techniques were phased in the operations to automatically track the landmarks and gradually augment the landmark grid as needed. This approach represented a great relieve on the workload and a significant improvement in accuracy.

2. Automatic landmark tracking

The mission was designed to reserve NAVCAM images slots for navigation purposes with one hour frequency minimum due to data link budget. This made impossible the use of feature detection algorithms based on corners or similar techniques that rely on the fact that the images in question are very similar in terms of observation conditions These techniques are not robust enough against long periods without images. After the time gap, the body's appearance might be completely different. Instead, a technique independent of the observation geometry was needed.

Small scale 3D high resolution maps(maplets) spread all around the body were created. Each maplet was centered on a landmark (an example is shown in Fig. 1). The technique employed is called stereophotoclinometry which consists in translating the grey levels of several images into slopes and then integrate the slopes into heights. This was first applied by R. Gaskell(ref [7]) to navigate near asteroid Itokawa and map it. The methodology, development and implementation details followed at ESOC were already presented in ref [3].

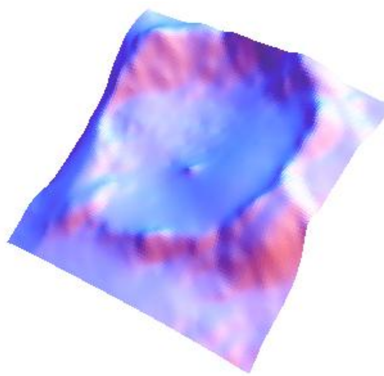

Figure 1. A 3D surface map of a crater on 67/P. The landmark is the rock standing in the center of the map.

The basic functioning of the technique is that given the 3D surface around a landmark, an albedo map and a photometric model, it is possible to predict a landmark visual appearance in any other observation conditions. Then, the predicted landmark appearance is cross-correlated with the real images and a landmark observation is obtained. The choice and tuning of the photometric model are presented in ref[1].

2.1. Maplet generation

The first process is the maplet generation which is the most difficult and time consuming. However once a maplet is generated it can be used to generate observations until a refinement is needed. On the other side obtaining observations is a much faster process.

Not all maplets associated to comet landmarks could be generated at the beginning. Only after there were sufficient images were a landmark was visible under different illumination conditions the maplet could be reconstructed.

Below, Fig 2 presents an example of all the images that were used to generate a particular landmark. As a first step images are rectified to appear as a local top view of the surface. For that it is a prerequisite to know the comet-S/C relative geometry at the times when the images were taken. To rectify an image, a preliminary surface is used: it can be just a flat plate if no information at all is available or a rough surface coming from a shape model.

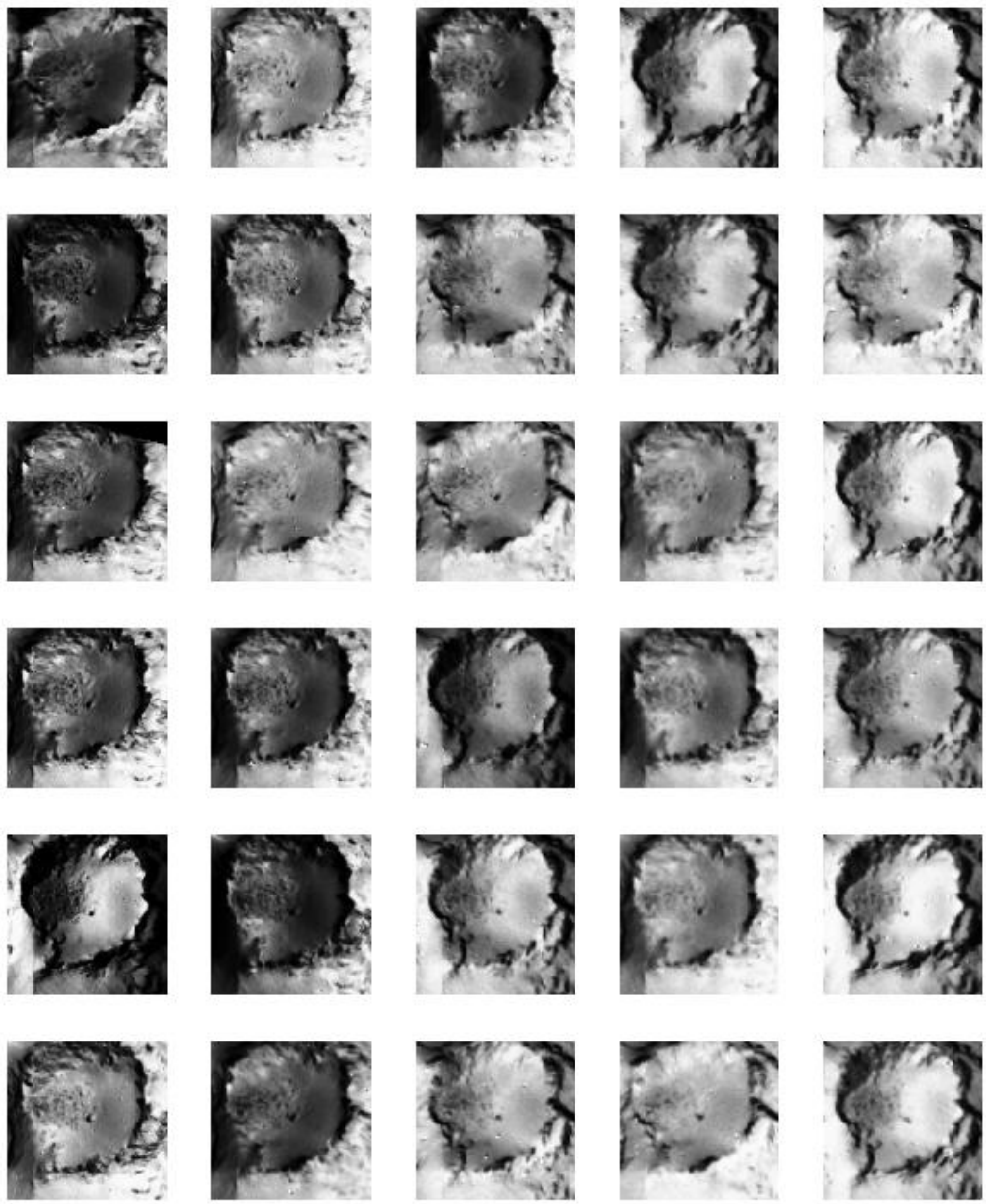

Figure 2. Montage of 30 rectified images that were used in the generation of a maplet.

The next step consists in inverting the rectified images into slopes and albedo maps using a photometric model. Finally the slopes are integrated into a height map. A height and an albedo maps constitute a maplet(example in Fig 3.). The height information is fed back to the image rectification step and the process advances iteratively until convergence is reached.

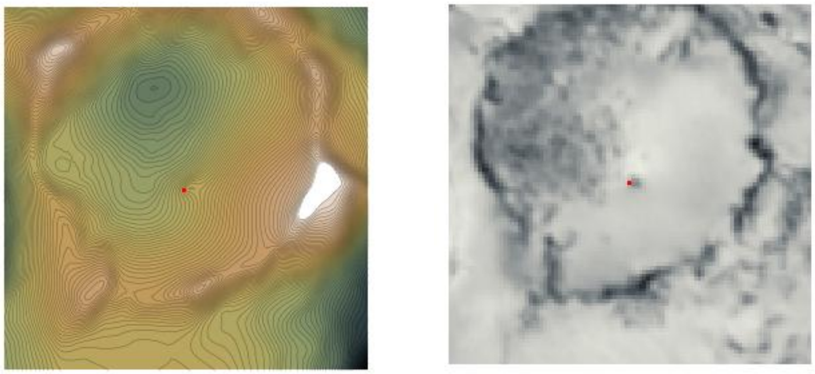

Figure 3. Maplet: height map(left) and albedo map(right).

Maplets should be generated such that a maplet cell size corresponds to a pixel at the distance in which it is planned to obtain observations. And at the same time the images used to generate the maplet had to be taken at that distance.

2.2. Landmark observation

Once a database of maplets is built using old images for which the geometry is known, every newly acquired image can be processed in the search for landmarks.

2.2.1 Image matching

Due to orbit and attitude prediction errors the appearance of the comet is in general different to what is expected. However, as long as the error in position is small compared with the distance to the comet and the attitude error is of a few millidegrees, the error can be first approximated as a shift in pixels in the x and y direction.

Before the actual landmark matching, an image matching step is required. The expected image is built using the database of maplets or with a shape model if available with the same photometric model that was used to generate the maplets. Then the true image and the simulated one are cross-correlated, the shift is computed and corrected. An image pair(real and simulated) is shown below in Fig. 4.

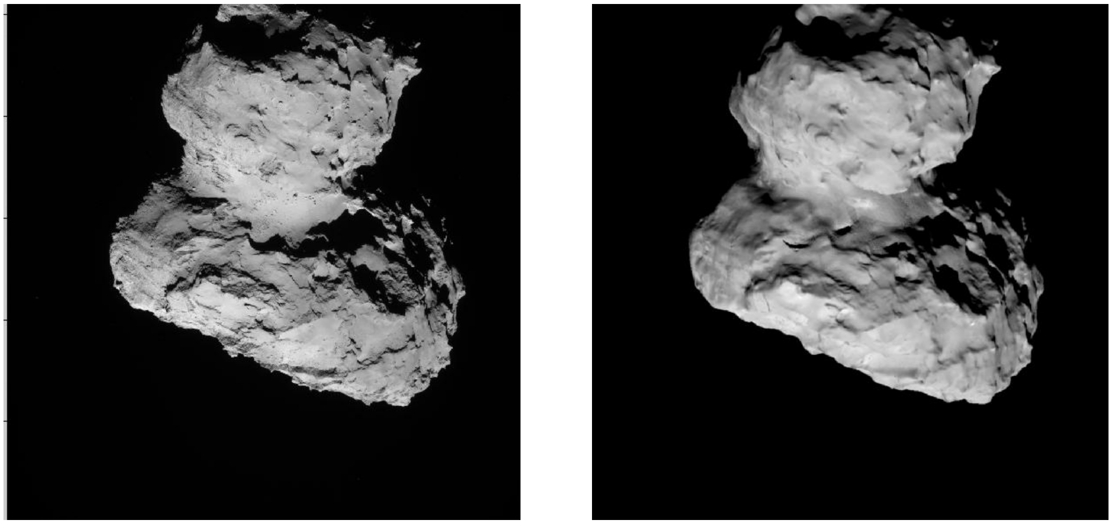

Figure 4. True image(left) and simulated image from a shape model(right).

2.2.2 Landmark matching

Since the image as a whole has been matched the main component of error has been removed and therefore the task of matching individual landmarks can be tackled. The difference between the expected landmark pixel coordinates and the truth should be of a few pixels. Similarly to the image matching step, a simulated rectified image(as illustrated in Fig. 5) is cross-correlated with the true rectified image obtaining the landmark observation pixel coordinates and uncertainty.

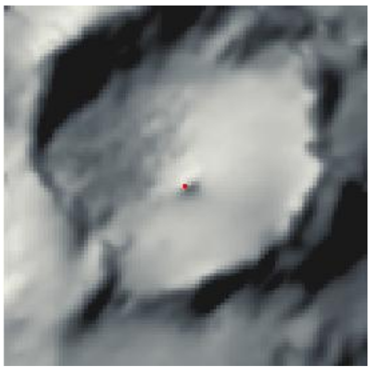

Figure 5. Simulated rectified image from a maplet.

This technique can achieve sub-pixel accuracy in the landmark pixel coordinates. These coordinates are converted into landmark directions in inertial frame using a camera model, the camera alignment and the S/C commanded attitude.

The range of applicability recommended in the literature for this technique is a maplet cell corresponding from one third of a pixel to three pixels. This constraint has always been applied to filter the images in the maplet generation process. However observations were obtained successfully even at a distance further than the optimum by a factor of 4.2. The lower constraint was never violated because the S/C never dived towards the comet in one go by more that a factor of two. Hence there was time to regenerate maplets based on newly acquired images before the subsequent dive.

Similarly photometric models are not supposed to be valid for very low phase angles(<10deg) or very high incidence and emission angles(>60deg). Though observations have been obtained without any noticeable decrease in quality for a range of phase angles between 0 and 130 degrees and emission and incidence angles between 0 and 90 degrees.

2.3. Observation validation

In a navigation analysis in ref [6] and [9] it was assumed that landmark measurements were determined to 1-pixel accuracy (1-sigma). Therefore a thorough observation validation scheme was put in place to remove outliers before they were delivered for orbit determination. An in depth paper was presented in [4].

The landmark positions and the S/C positions and orientations are estimated using the landmark inertial observations with a technique called bundle adjustment. This method is purely geometrical therefore it can be decoupled from the orbit determination. Since the solution has seven degrees of freedom, it has to be constrained arbitrarily and then mapped once with a translation, rotation and scale factor to the true solution from the orbit determination solution.

The a priori knowledge of the landmark positions is very good because they have been refined with every new image and the S/C attitude is known with an uncertainty of ~10 millidegrees. Therefore the S/C position can be estimated with good precision and the quality of the observation can be assessed with the resulting residuals. Outliers are found and removed this way.

Additionally the output of this process is useful for two more reasons. First, the knowledge of the landmark positions improves and if any new landmark was observed more than three times its position is estimated for the first time. And finally because the S/C relative geometry at the times when the images were taken is resolved allowing to augment the image database for future maplet generation.

3. Shape reconstruction

An operational shape model is of scientific interest, but it was also required for a number of important operational reasons, namely: improvement and acceleration of the algorithms for landmark tracking, image matching during night excursions by limb fitting(ref [8]) as illustrated in Fig. 6, image simulation, estimation of gravity model and cross-check against the output from the orbit determination, evaluation of landing site candidates, Philae trajectory reconstruction (ref [2]) and correlation with comet atmosphere data from instrument ROSINA.

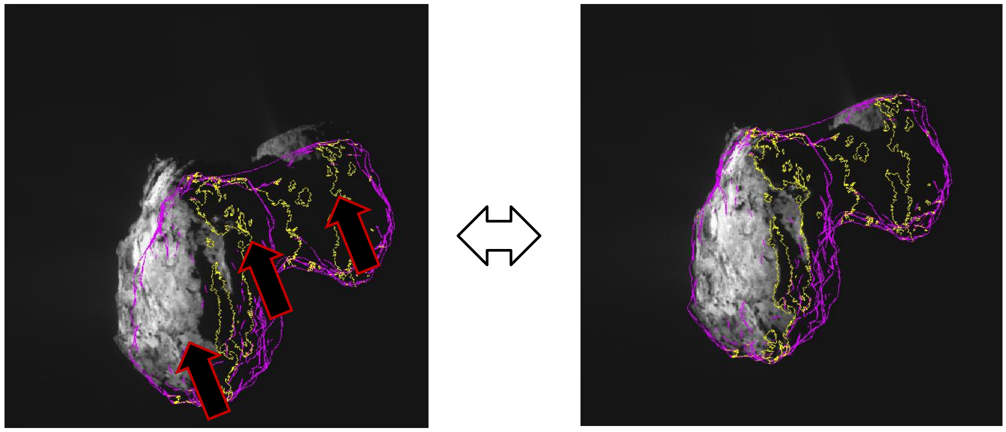

Figure 6. Limb fitting

3.1 Silhouette carving

The operational shape model was reconstructed at the beginning of the Comet Characterization Phase using a technique called silhouette carving. Iit kept improving as more images were available as can be observed in Fig. 7. This technique consists on building a notably bigger volume than the expected comet shape, and then sequentially removing pieces of the volume that are not part of the body as seen from the pictures(the implementation details were published in ref [5]) Therefore, the result will be a conservative shape that contains the true shape. The silhouette carving alone cannot carve within concave regions.

Due to the orientation of spin axis of the comet, the southern latitudes were for several months in the dark. Therefore these areas were not well characterized until the Extended Monitoring Phase was reached.

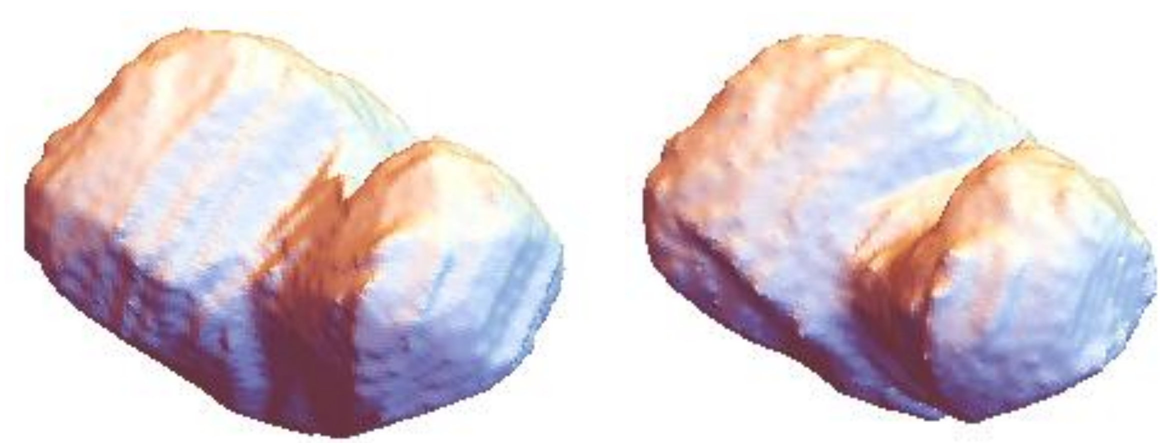

Figure 7. Shape model from silhouette carving. After a few revolutions(left) and after a few weeks(right)

3.2 Maplet assembly

Finally maplet coverage of most visible areas of 67/P was achieved. This information was used to assemble the maplet collection into a high resolution shape model that could be relied upon up to the maplet resolution if needed. However most applications demanded less resolution due to memory and computation time.

Figure 7. Shape model from maplet assembly.

4. Mission Phases

The objectives and particularities of the different missions phases regarding optical navigation will be presented in following subsections.

The Rosetta S/C is equipped with a set of 2 navigation cameras (NAVCAM). In addition two science cameras, the OSIRIS narrow angle camera (NAC) and the OSIRIS wide angle camera (WAC). The OSIRIS cameras were meant for science purposes and are not operational instruments. The navigation was based on use of NAVCAM data only. However during far approach and lander delivery NAC images were also available in cooperation with the OSIRIS team and also regular WAC images were delivered for navigation robustness.

	CAM	**NAC**	**WAC**
Field of view [deg]	5 x 5	2.20 x 2.22	11.35 x 12.11
Pixels	1024 x 1024	2048 x 2048	2048 x 2048

Table 1. Rosetta cameras properties.

4.1. Comet characterization

On August 8th 2015 Rosetta arrived at the comet and the initial characterisation phase began. Its main objectives were to identify landmarks on the comet surface and estimate their position, to determine the rotation state of the comet and its shape and to obtain a first estimate of the gravity potential, allowing for future navigation of smaller orbits around the nucleus.

In order to achieve the above objectives Rosetta obtained full images of the nucleus every hour with a relatively wide variety of observation conditions. The spacecraft was placed at a distance of between 90 and 120 km from the nucleus in order to contain the comet largest diameter.

During the first days a first set of around 50 landmarks were identified visually in the comet surface with the help of a GUI as shown below in Fig 8. These landmarks were evenly distributed over the north hemisphere of 67P which was illuminated at the time.

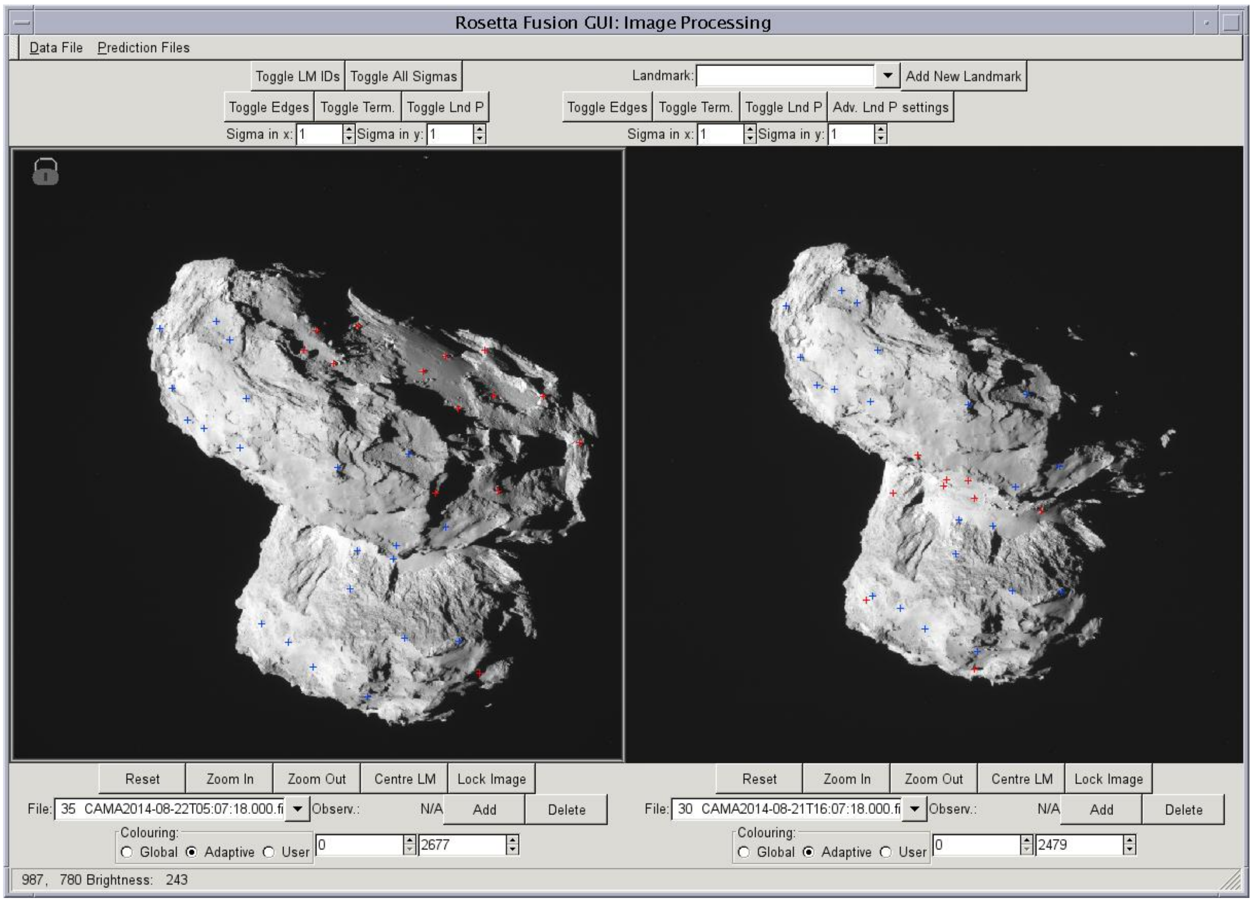

Figure 8. Image processing GUI with visual landmark observations.

The observations were processed to determine the relative position and orientation between S/C and comet and to estimate the landmark coordinates on the body as mentioned in section 2.3. This processing resulted in a data base of images where the relative geometry was known. Simultaneously a first coarse comet shape model reconstruction was carried out using silhouette carving as explained in section 3.1. By August 13th 2015 Rosetta had observed 67P with phase angles from 30 to 50 degrees and comet latitudes 85 to 0 degrees.

At this stage the first set of maplets was generated. This initial maplets had a 10 meter resolution in a 99 x 99 cell grid and started to produce observations. Automatic landmark tracking started to be used in the background using as an input the image database, the landmark coordinates and the shape model. Maplet observation quality was assessed and visually checked while the s/w configuration was fine-tuned. After a few weeks operators confidence grew on the maplet observations and the technique was phased into the daily procedures. Initially operators would obtain automatic observations of known landmarks and visually confirm them. However the task of identifying new landmarks and estimate their position was left to the operators for a few more weeks before it also became automated.

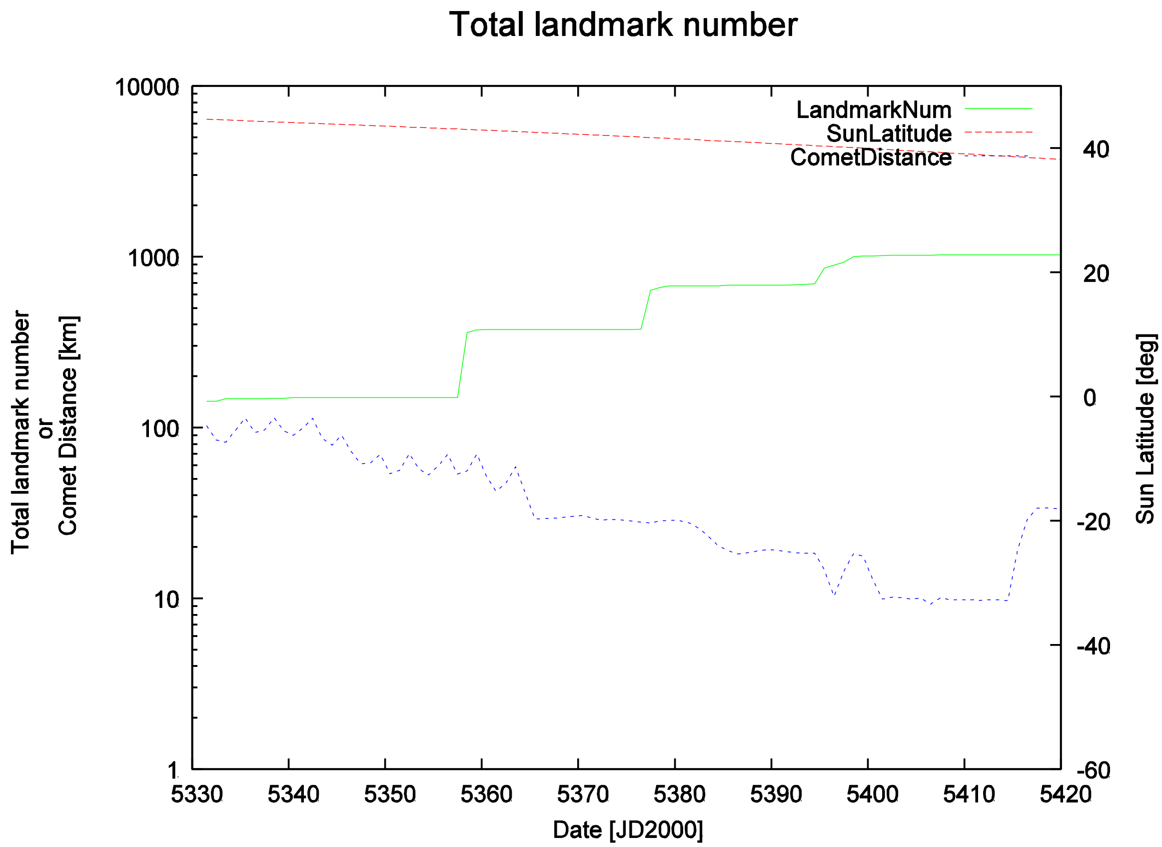

Figure 9. Total landmark number in the first months.

After an initial period of 12 days, the distance to the nucleus was reduced to 50-70 km to allow for observations with better resolution. Since the nucleus did not fit in a single image, it was then decided to acquire arrays of 2x2 images at a time to form a raster but reducing the image periodicity to four hours in order to keep the same data volume but doubling the effective field of view. This approach was also more robust against off-pointing due to errors in the dynamic propagation. For the same reason WAC rasters were scheduled twice a week which have similar resolution as the NAVCAM images but the FoV is double. For all following analysis rasters are considered as single images even though each image has been processed individually.

For this distance a second set of maplets was generated with 5 meter resolution after enough images were gathered at 50 km distance.

4.2. Global mapping

At the end of the initial comet characterisation phase, initial estimates of the gravity potential of the comet, landmark positions, comet rotation state and shape were obtained however it was required to observe the body at closer distances to further improve the knowledge about it. In addition it was necessary to map 67P with higher resolution to allow accurate navigation in the subsequent phases leading to lander delivery. Closed orbits were achieved at 30km distance at phase angles between 60 and 120 degrees. After few days at this lower altitude a third set of maplets was produced with 3 meters resolution.

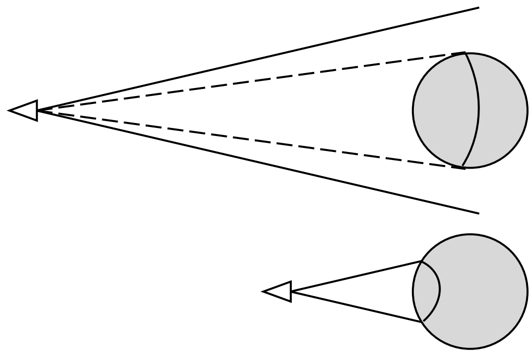

Figure 10. Sketch showing the comet visible area.

If landmarks were evenly spread on a sphere the proportion of the visible area to the total surface area is a function of the distance to the centre, d, the sphere radius, R, the field of view, FoV, and the phase angle, Φ. This proportion drops very steeply once the object exceeds the camera field of view as sketched in Fig 10. The theoretical observable area is expressed below:

$$f = \frac{1}{2}\left(1 - \frac{R}{d}\right) \qquad \forall\, Asin(R/d) \geq FoV$$

$$f = \frac{1}{2} \cdot Cos^2(FoV) \cdot \left(1 + \left(1 - \frac{d}{R}\right) \cdot Tan^2(FoV) + \sqrt{1 + \left(1 - \left(\frac{d}{R}\right)^2\right) \cdot Tan^2(FoV)}\right) \qquad \forall\, Asin(R/d) < FoV$$

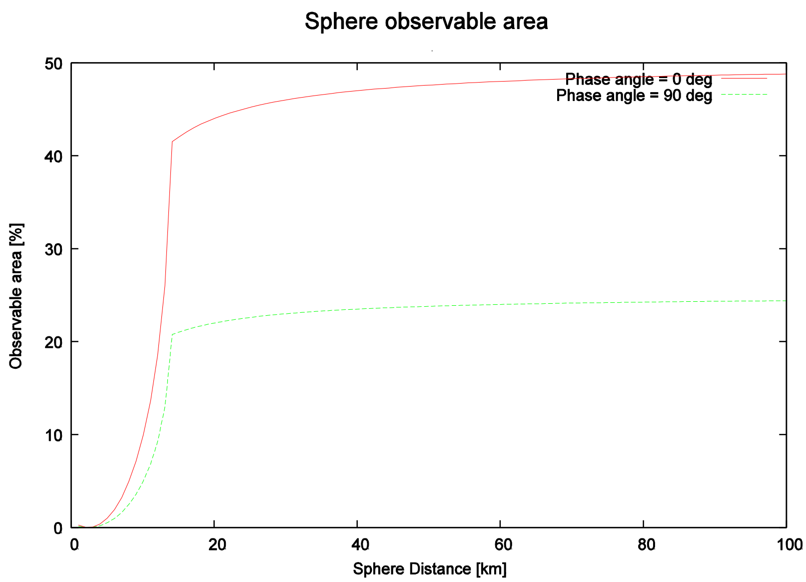

Figure 11. Visible area of a sphere of equivalent radius to the comet mean radius and FoV equivalent to a NAVCAM raster FoV.

From the navigation analysis, in ref[6] and [9], the initial target for the number of landmarks to achieve accurate navigation was one hundred. Since the theoretical maximum number of observations when flying terminator orbits was around 20, a target of 15 observations per image or raster was established. This constraint was always fulfilled in the daily average of observations per image (Fig 9) even though some occasional images fell below the target.

However this had to be carefully planned by anticipating the drop of observations that would occur when approaching the comet and increasing the phase angle. In preparation of these cases, the landmarks density was always increased in advance, as proven in Fig. 12. The date is expressed in JD2000 which is a convention at ESOC defined as the Julian day with epoch in January 1st 2000. All following dates will be in the aforementioned time scale.

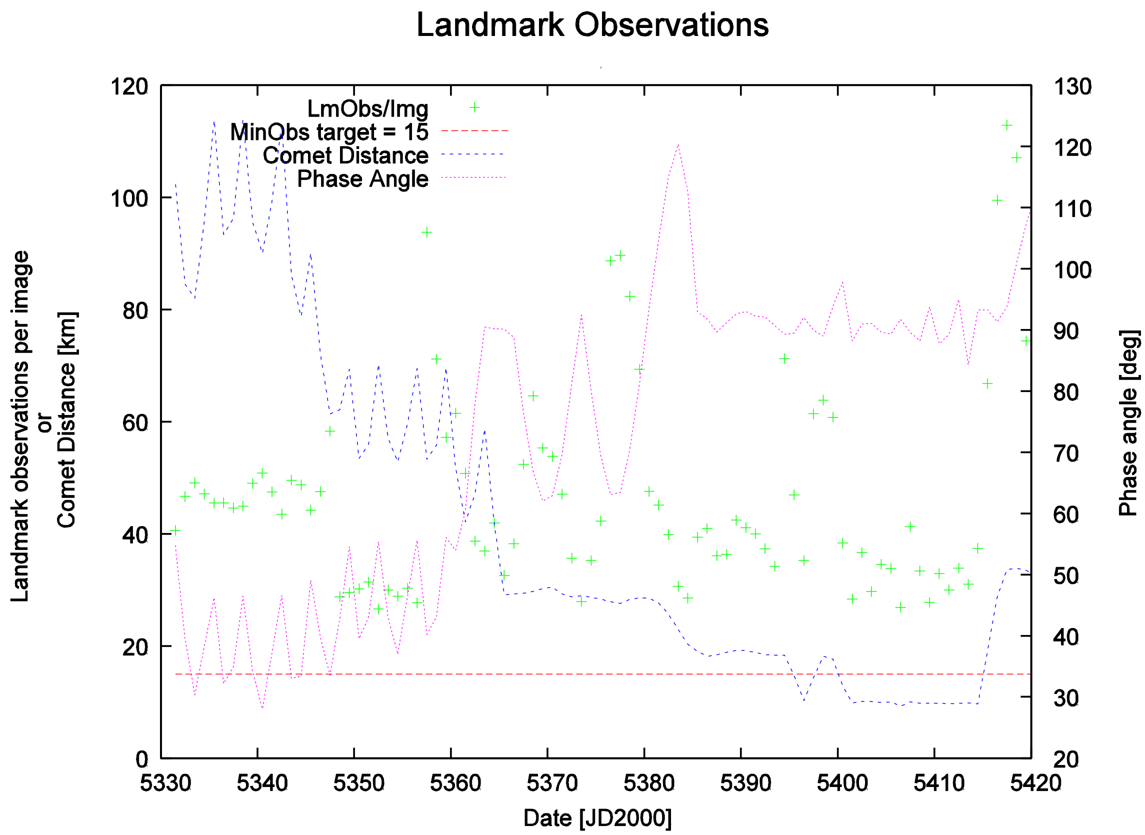

Figure 12. Landmark observations in the first months.

4.3. Close observation

At completion of the global mapping, potential landing sites on the comet surface were proposed by the lander community. The landing sites were observed from closer distance to assess their suitability. The trajectory described 20 km circular terminator orbits and finally the distance to the comet centre was reduced to 10 km. The last two sets of maplets were generated during this phase with 2 meters and 1 meter resolution respectively.

Obtaining landmark observations at very low distances to the comet would have been very challenging for an operator because the body silhouette is generally outside the field of view and the largest features appearance cannot be easily mapped to what they looked like at further distances. Additionally, at these distances the required amount of landmarks was over a thousand but a human cannot handle more than a few tenths of landmarks without additional help and extreme effort.

On the other side automatic landmark tracking was still possible. Nonetheless this method seemed at the edge of its capacity because it started to suffer from too high pointing errors that affected the efficacy of the image matching. About one forth of the images were not matched correctly at this height. The reason was that the same orbit propagation errors translated into higher angular errors at low distances. And at the same time the propagation was degraded by higher comet atmospheric drag and higher order gravity potential terms.

4.3. Landing

The objective of this phase was the delivery of the lander in the comet surface. In terms of optical navigation this phase was not different from the previous phases except for observing the Philae during its descent and landing for lander trajectory reconstruction purposes. This was done visually with a GUI the same way landmarks were identified in section 4.1. More details about the landing reconstruction were published in ref[2].

4.4. Extended monitoring Phase

After lander separation and commissioning, the extended monitoring phase started where the S/C escorted the comet to analyse its evolution while approaching perihelion. This represents the longest phase of the mission that started in January 2016 and is planned to last at least until mid 2017. During this phase the trajectory served science purposes for some months performing night excursions and nucleus close flybys. Finally due to comet activity the distance was gradually increased to protect the mission.

After all this months of operations plus the previous mission phases all the data, results and statistics could be put together and analysed. Conclusions about the automatic landmark tracking performance can be derived as well as explain the rationale for the approach employed.

In Fig. 13 the evolution of the total number of landmarks is presented along with the comet distance and the sun latitude. It can be observed how the number of landmarks were increased always before a significant drop in distance was performed. However after the close observation phase the number of landmarks increased slowly as the sun revealed new illuminated areas in the southern latitudes.

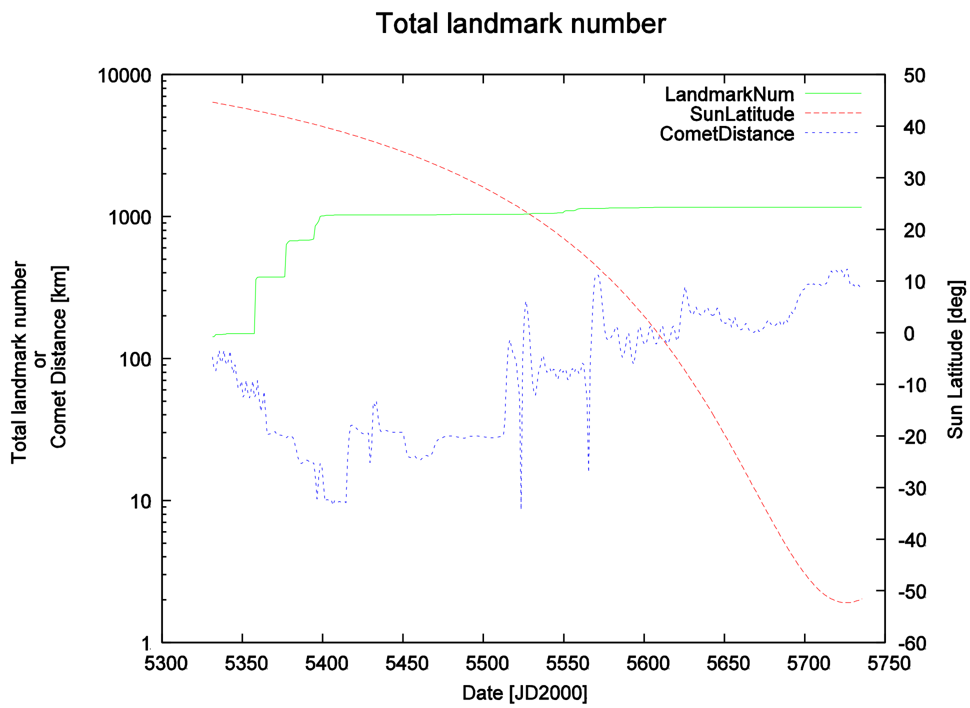

Figure 13. Total landmark number.

In Fig. 14 it can be observed that after the close observation phase the full comet was observable on the images or images rasters and the amount of landmark observations per image remained stable with respect to the comet distance but was very sensible to changes in phase angle.

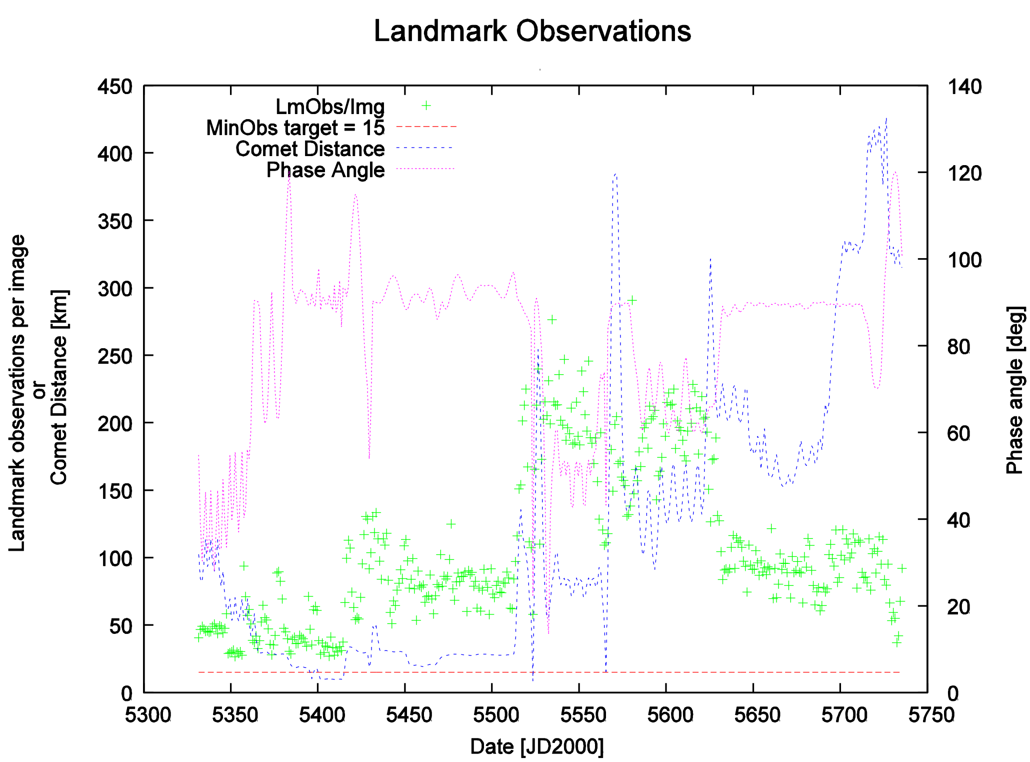

Figure 14. Total landmark observations.

Fig. 15 and 16 stress the relationship between the fraction of landmarks observed ant the maximum theoretical values as a function of distance and phase angle.

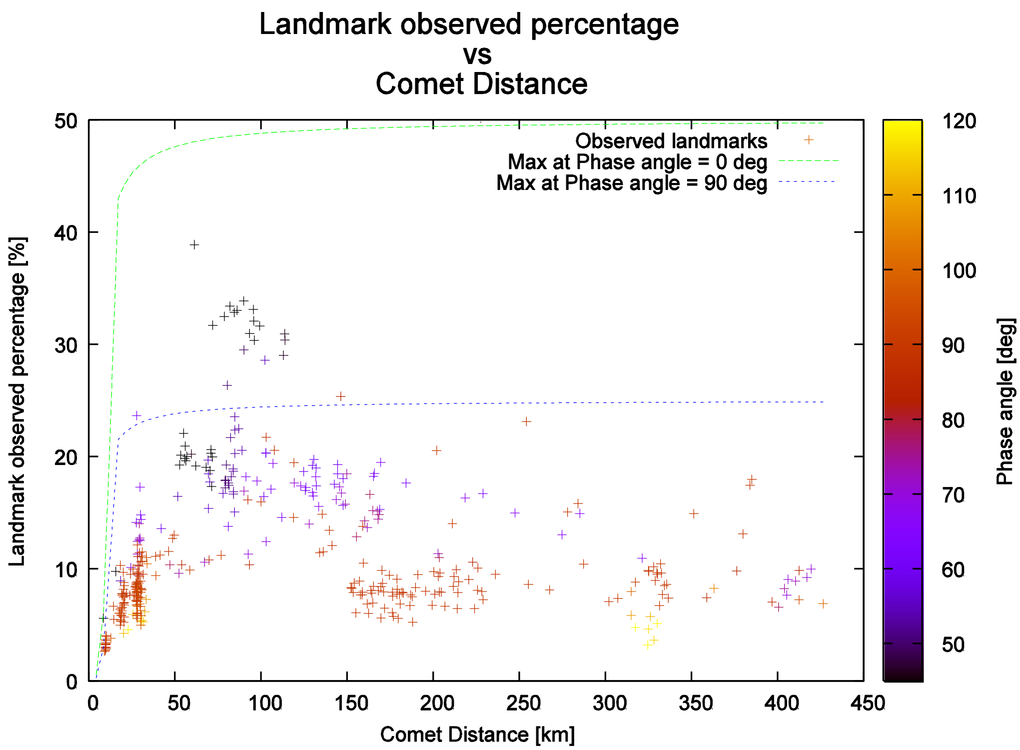

Figure 15. Landmarks observed vs. distance.

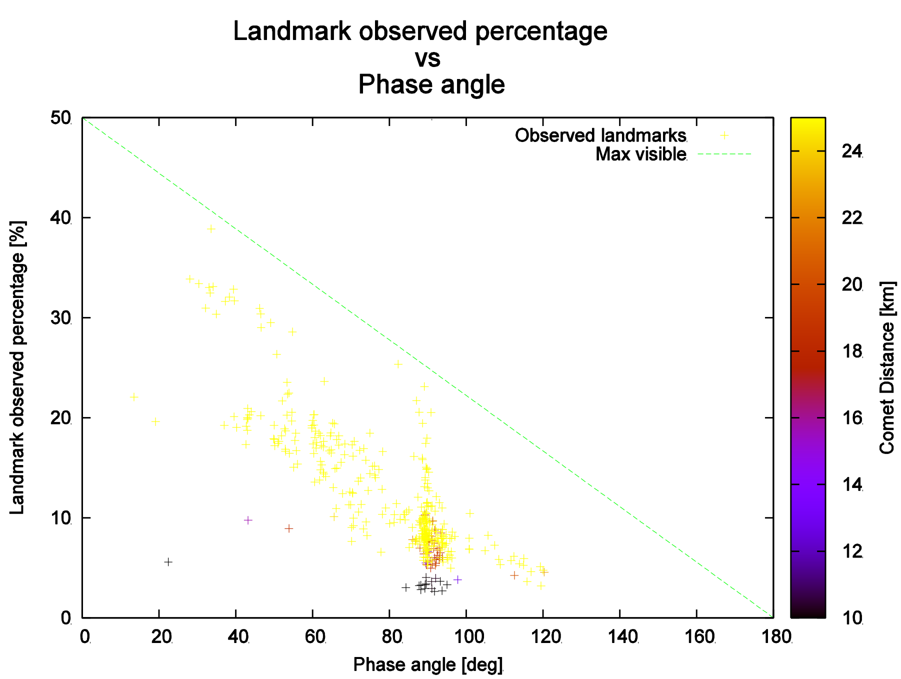

Figure 16. Landmarks observed vs. phase angle.

4.4.1Flybys

The results of a close flyby have been selected for being a particularly challenging optical navigation scenario. The comet distance ranged from 250 km to 10 km and the phase angle from 90 to 0 degrees.

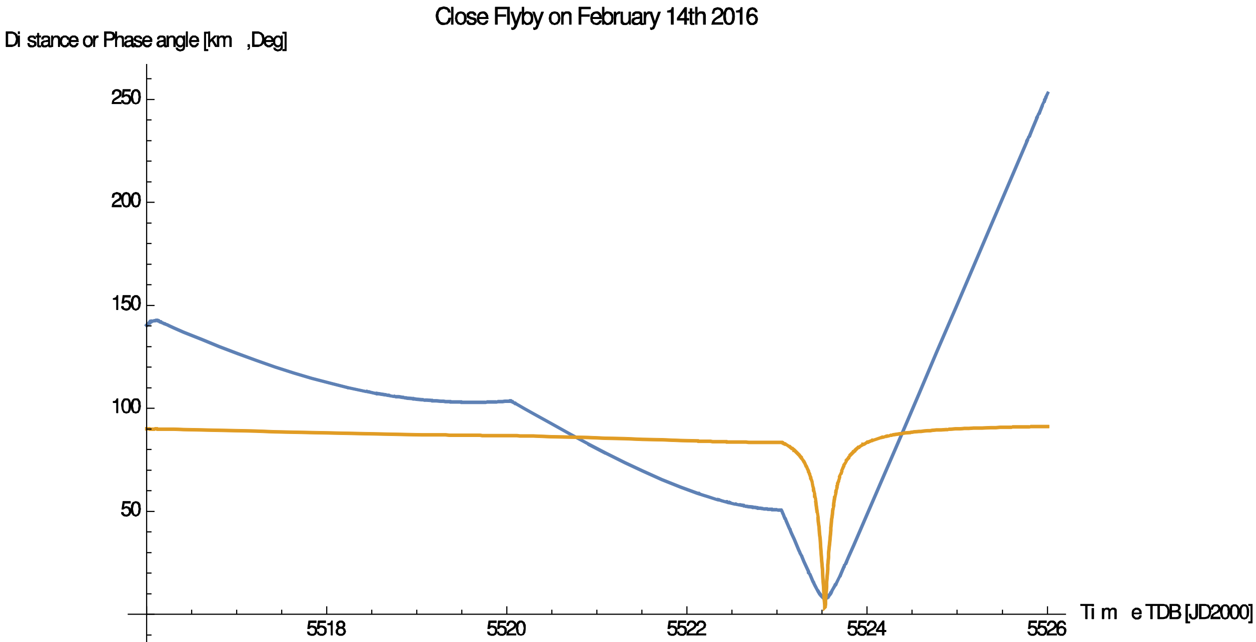

Figure 17. Flyby on February 14th 2016 distance and phase angle.

Five sets of maplets had been obtained up to this mission phase with different resolutions. All five sets were used during the flyby to cope with the fact that the comet distance changed by a factor of 25. These sets had been gradually generated during the pervious mission phases as the S/C lowered its height step by step. The rules in Table 2 were implemented for the s/w to automatically select the maplet set most suited for the expected distance to the comet at each image. This way it was ensured that the maplet technique was not used outside its range of applicability.

	Distance to the comet [km]		
Maplet set number	**Lower limit**	**Upper limit**	**Cell resolution [meters]**
1	0.0	15.0	10
2	15.0	25.0	5
3	25.0	40.0	3
4	40.0	70.0	2
5	70.0	300.0	1

Table 2. Maplet set choice rules.

During the flyby 195 images were processed in 10 days. 14331 landmark observation were obtained and validated representing 57% of all theoretically possible landmarks observations. The remaining 43% were not successfully matched or filtered out based on numerous quality criteria. The results of the bundle adjustment provide valuable landmark tracking assessments.

This estimation process used 28622 measurements to estimate 4275 variables obtaining RMS(residual) = 3.5 millidegree(or 0.7 pixel). The residuals presented below in Fig. 18 show a smooth distribution without degrading its accuracy with the distance nor the phase angle. Additionally as presented in Fig 19 the normalized residuals have a root mean square very close to one, confirming the a priori estimation of the observations uncertainty.

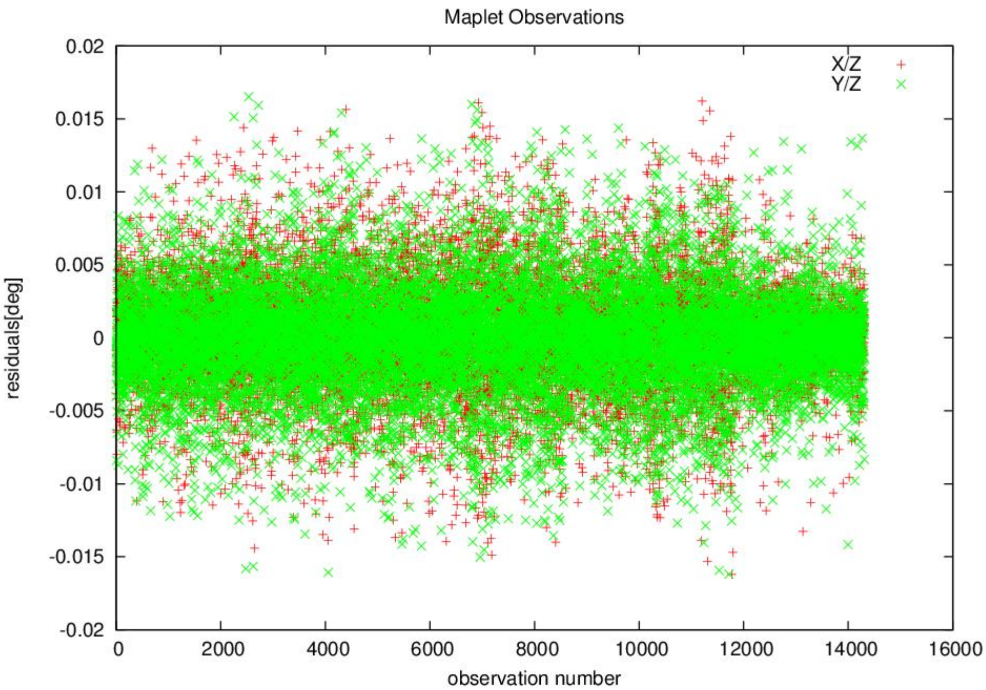

Figure 18. Maplet observation residuals.

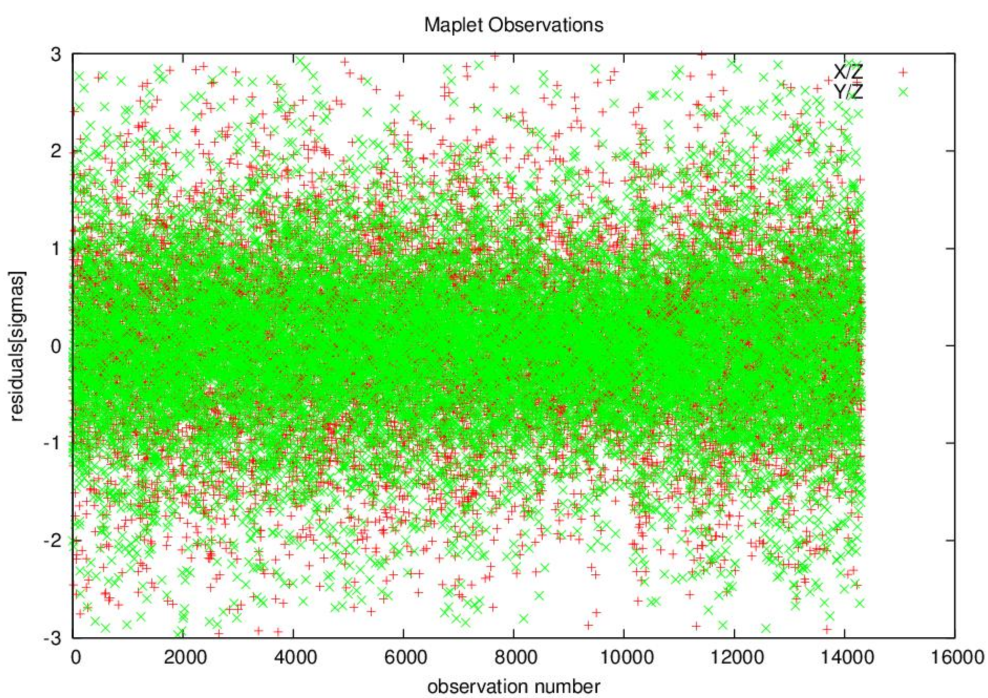

Figure 19. Maplet observations normalized residuals.

6. Conclusions

The Rosetta mission carried out successfully optical navigation near the comet 67P/Churyumov-Gerasimenko for over a year of operations covering a range of distances from 10 to 450 km and a range of phase angles from 0 to 120 degrees. In that period, 1157 landmark were defined on the surface of comet and were daily observed in 6280 images. Images were acquired with a frequency from 4 to 24 per day. A total of 372000 landmark observations were obtained using the maplet technique.

The maplet based optical measurements of landmarks were automated on-ground relieving vastly the workload. The initial scheduled man power consisted on four operators identifying landmarks visually four hours a day, seven days a week. However the current review and assessment of the image processing requires 15 minutes for a single operator only during normal working days.

Maplets observations achieved consistently sub-pixel accuracy through out all mission phases. The observations RMS(residual) ranged from 0.6 to 0.8 pixels or from 3 to 4 millidegrees. Observation validation and filtering schemes were found key to the smooth functioning of this technique.

The shape of the comet was accurately reconstructed by assembling the full set of maplets into a 1.7 million facets polyhedron with ca. 9 meters horizontal resolution. The shape gradually improved as new areas of the comet were illuminated by the Sun achieving by June 2015 full shape model coverage.

7. References

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