ROSETTA NAVIGATION DURING LANDER DELIVERY PHASE
AND RECONSTRUCTION OF PHILAE DESCENT TRAJECTORY AND REBOUND

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Abstract: *After ten years of interplanetary flight, ESA's Rosetta spacecraft arrived at its final destination, comet 67P/Churyumov-Gerasimenko, on August 6th 2014. The first three months around the comet were dedicated to its characterization and to the identification of candidate landing sites for the Philae lander. On November 12th, Philae separated from Rosetta, starting its 7-hour descent to the target landing site: Agilkia. Philae's telemetry, received on ground via Rosetta, confirmed that landing occurred at 15:34:04 (UTC, on-board time), but also that Philae did not succeed to anchor to the comet surface. This caused the lander to bounce and continue an additional 2-hour flight, in which it collided with a crater rim; it had another smaller bounce; until it finally landed on the comet surface, where it successfully executed its primary science mission. In this phase, Rosetta navigation was very demanding in terms of operations workload and required navigation accuracy. It is considered a success, since all operations could be conducted nominally and the first landing point was well within the a priori landing error ellipse. This paper presents the Rosetta navigation during the first-ever soft landing on a comet, describes the trajectory flown during the Lander Delivery phase, the achieved navigation results and landing accuracy, as well as the performed reconstruction of Philae's descent, touch-down point, rebound, and the subsequent flight over the comet's surface.*

Keywords: *Rosetta, optical navigation, comet landing, descent trajectory reconstruction.*

1. Introduction

1.1. Rosetta Mission

Rosetta is an interplanetary cornerstone mission in ESA's long-term space science program. Its main objective is the exploration and study of comet 67P/Churyumov-Gerasimenko during its approach to the Sun. The spacecraft carries 11 scientific instruments and a lander module, Philae, with 10 additional instruments, for the most detailed study of a comet ever attempted.

Launched in March 2004 with an Ariane-5/G1, it used 4 planetary swing-bys (Earth [1] and Mars [2]) in order to obtain the required velocity to reach the orbit of the comet. During its long journey, Rosetta had close encounters (fly-bys) with 2 asteroids: (2867) Šteins [3] and (21) Lutetia [4].

Rosetta arrived at the comet on August 6th 2014. Since then, it has been flying around it to study its characteristics and activity evolution during its approach to the Sun. On November 12th, Rosetta delivered the lander Philae into its descent trajectory to the comet's surface, and served as relay to establish a communication link between Philae and Earth. On August 13th 2015, the comet passed through its perihelion and, some time after that, its activity started decreasing. Rosetta will continue escorting the comet on its way to the outer Solar system until end of September 2016, when the end of the mission is planned.

1.2. Rosetta Spacecraft

Rosetta is a box-shaped spacecraft of sizes 2.8 m x 2.1 m x 2.0 m, with a 64 m^2 solar array and a steerable 2.2 m diameter high gain antenna. The spacecraft is 3-axis stabilised, controlled with reaction wheels and/or thrusters (depending on the mode) and using star trackers and laser gyros as attitude sensors. It is equipped with 4 optical cameras that can be used for relative navigation: 2 redundant navigation cameras (NAVCAMs) and 2 cameras from OSIRIS [5] scientific instrument: NAC (Narrow Angle Camera) and WAC (Wide Angle Camera).

1.3. Philae Lander

Philae lander's body measures about 1 m × 1 m × 0.8 m (with its landing gear folded) and is covered with solar cells. It weighs 100 kg of which 26.7 kg are scientific payload. The platform for landing is equipped with: a flywheel for 1-axis attitude stabilization, a deployable landing gear capable of absorbing kinetic energy at touchdown; a cold gas thruster to push the lander towards the comet surface, ice screws in its three legs, and harpoons to anchor it to the comet's surface.

Figure 1. Rosetta spacecraft (left) and Philae lander (right)

1.4. Landing Site Selection

Once Rosetta arrived at the comet and started collecting close-up information, the Landing Site Selection Process was initiated. It involved the European institutions ESA, DLR and CNES, and the scientific community, with the objective of selecting the target landing site that simultaneously met scientific goals as well as operational constraints and technical feasibility. First, a list of 10 landing sites was elaborated, named from "A" to "J". It was later reduced to 5 candidate sites, and finally, on September 15th, the selection of "J" as the primary landing site was announced. Weeks after, as an outcome of a public contest, “J” was renamed to Agilkia, after an island on the Nile River in the south of Egypt. Agilkia is located in the smaller lobe of the comet, at 14.7 degrees latitude and -27.0 degrees longitude, next to the big crater on the smaller lobe.

1.5. Summary of Landing Events

The lander delivery sequence started on November 12th 2014, 9.5 hours before landing, with the execution of the pre-delivery manoeuvre. Telemetry data and 2-way Doppler tracking had to be rapidly assessed to confirm the accurate execution of the manoeuvre, resulting in the final go for separation. Afterwards, the spacecraft slewed to the separation attitude and Philae was ejected from Rosetta at a comet distance of 22.6 km. The ballistic descent of Philae lasted 7 hours with no means to control its trajectory. During descent and after touch-down, Rosetta used its optical cameras to take images of the lander, which confirmed the proper deployment of its landing gear and later were useful for reconstructing the lander trajectory. Philae’s telemetry, which was received on ground via Rosetta, confirmed that landing occurred at 15:34:04 (UTC, on-board time). The cold gas thruster, the harpoons, and the screws in its legs that, ideally, would have anchored it to the comet surface did not work properly. It was already known before separation that the cold gas system could not be used due to a failure in the pressurization valves, and later, it was learnt that the harpoons did not fire at touch-down. This caused the lander to rebound but, thanks to the damping mechanism of the landing gear, a big part of the kinetic energy was dissipated, preventing the lander from escaping the comet’s gravity. Philae continued an additional 2-hour flight, until it finally landed on the comet’s surface where it successfully executed its primary science mission [6].

2. Design of Lander Delivery Phase

2.1. Description

Rosetta’s Lander Delivery phase (SDP) started on October 28th with the execution of SDP-1 manoeuvre that drove the spacecraft away from the “Close Observation” 10-km orbit, in a transition arc to the 30-km parking orbit, in preparation for the lander delivery sequence to be executed on November 12th. The main objectives of this phase were: to safely deliver Philae into its descent trajectory towards the target landing site; to keep the communication link with the lander during descent and immediately after landing; and additionally to take images of the lander’s descent and landing.

2.2. Trajectory

Figure 2 shows, in white, the terminator orbits flown by Rosetta the month before lander delivery (from 20 km to 10 km distance); and in red the trajectory flown by Rosetta for lander delivery:

(1) Rosetta is inserted in a circular 30-km parking orbit with an orbital plane tilted 15 degrees from the terminator plane (plane separating day/night). Rosetta flies almost a full orbit revolution around the comet, half of it spent in the night side of the comet (2). Once Rosetta arrives at the target point (3) for the initiation of the lander delivery sequence, the pre-delivery manoeuvre

(83.6 cm/s) is executed, driving the S/C in a hyperbolic trajectory, almost in collision course, with 5 km miss-distance. A mission constraint did not allow to drive the orbiter in a collision trajectory to the comet, even if the plan included a subsequent manoeuvre that would avoid the collision.

At a distance of 22.6 km (4), Philae separates from Rosetta. The nominal separation's relative velocity was 18.76 cm/s. Taking into account the mass of Rosetta and Philae and the fraction of Rosetta's propellant intervening in the separation, it results that, nominally, the lander would receive a ΔV of 17.4 cm/s and Rosetta of 1.1 cm/s. The ΔV received by the lander redirected its trajectory towards the target point on the comet's surface. The direction in which the separation is performed fixes the orientation of the lander's Z-axis, which is stabilized by the angular momentum stored in its flywheel. The descent trajectory was designed such that at touch-down (7 hours after separation) the lander's Z-axis was parallel to the local vertical (defined as the normal to the local surface), and that the incoming relative velocity with respect to the surface was also parallel to the local vertical.

In the meantime, Rosetta executes the post-delivery manoeuvre to avoid passing at 5-km distance from the comet, staying in the day side of the comet and ensuring communications with Philae during descent. Philae's antenna is mounted pointing along lander's +Z axis and, by design, it is not pointing to Rosetta after separation. Therefore, a communication link during descent would not be possible if Rosetta did not execute the post-delivery manoeuvre. Afterwards, the mission enters in the Relay Phase (5), in which Rosetta performs a series of manoeuvres to keep its trajectory in the region where the lander visibilities durations are maximized, in order to support the scientific operations of the lander on the comet's surface.

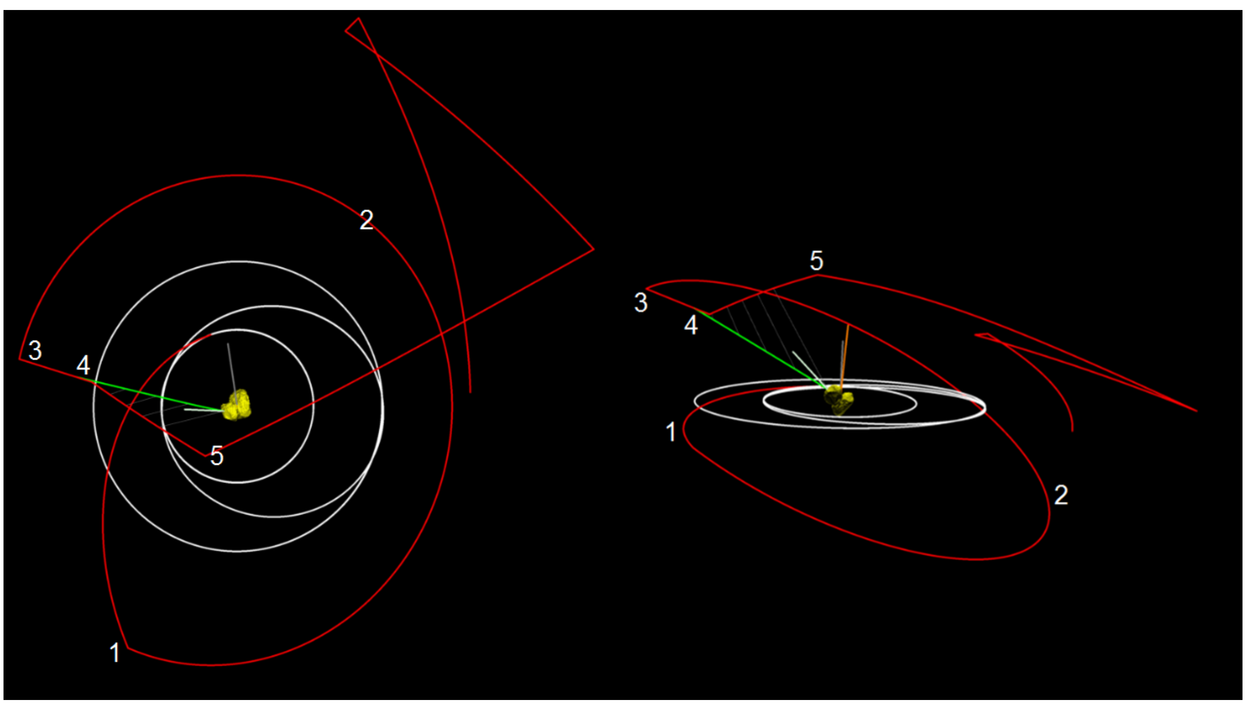

Figure 2. Lander Delivery trajectory: Rosetta (red), Philae (green). Views from Sun direction (left) and close to the terminator plane (right)

2.3. Navigation Analysis

In the scope of the design of the lander delivery trajectory, navigation analysis was performed to assess the achievable landing accuracy. Monte Carlo simulations were run reproducing the navigation process: randomly generating a "real-world" trajectory; based on it, simulated observations are generated and fed to the orbit determination (OD); from the OD solution, the landing trajectory is optimized; and finally, the resulting manoeuvres and separation conditions are perturbed and applied to the real-world to propagate the trajectory and compute the achieved landing point.

The results of this analysis showed that the landing uncertainty was covering an area of roughly 500 m radius around the target landing point and that the uncertainty in the landing time was of about 40 min. Figure 3 shows the landing points of several simulated trajectories plotted on top of a NAVCAM image [7].

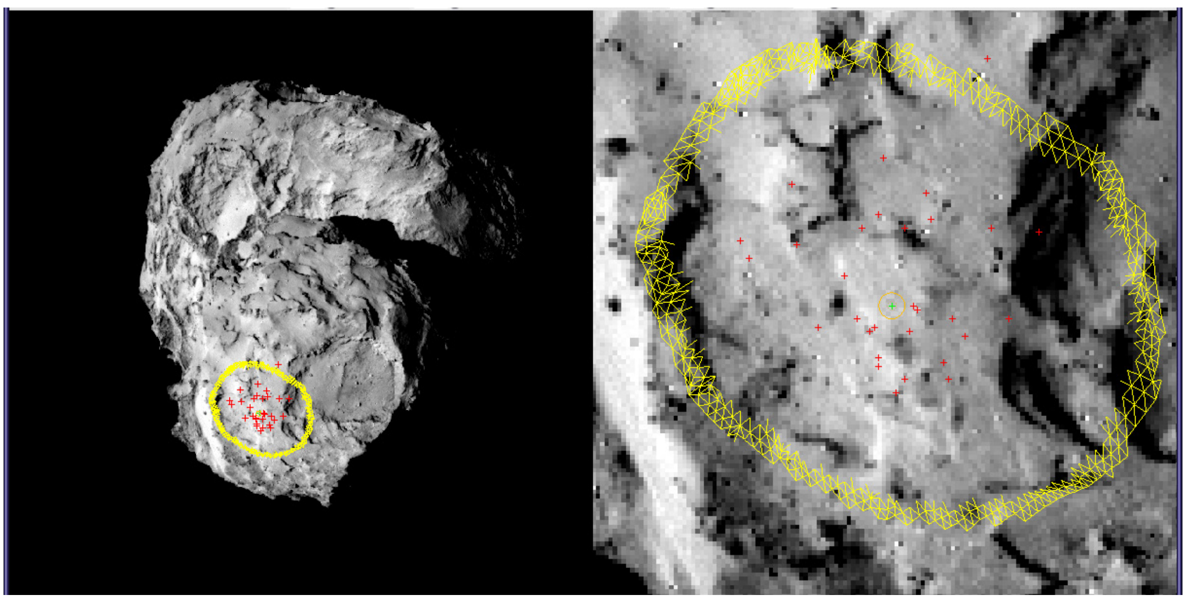

Figure 3. Landing points of simulated trajectories plotted on top of a NAVCAM image

3. Rosetta Navigation during Lander Delivery Phase

Rosetta navigation around the comet is based on radiometric tracking (2-way Doppler and range) plus landmark observations reduced from the optical images of the comet's surface taken by the on-board cameras. Rosetta orbit determination (OD) is performed using the ESOC interplanetary orbit determination system [8] [9] that was enhanced, during the spacecraft's hibernation period for the Rosetta comet phase, to support simultaneous estimation of comet orbit, comet attitude and Rosetta orbit using as relative measurements landmarks identified in optical images [10].

3.1. Estimation of Comet's Physical Parameters

As a preparation step for the Rosetta navigation during Lander Delivery phase, a long-arc OD was run to obtain the best estimate of the comet dynamic/physical parameters: orbit, spin axis direction, rotation period, gravitational parameter and gravitational field expansion in 3x3 spherical harmonics, centre of mass location, and landmark coordinates [9].

The OD performed at each commanding cycle was a short-arc OD in which all these parameters were fixed, treated as consider parameters with estimated values and uncertainties obtained from the long arc OD. This approach simplified the operations during the busy days of spacecraft commanding, while allowing for high accuracy navigation.

The long-arc OD spanned over September and October, when Rosetta was between 30-km and 10-km distance, in the Global Mapping and Close Observation phases. The orbit at 10-km radius provided the most relevant information for the estimation of the comet parameters. Since after that, Rosetta was leaving to higher distances (30-km parking orbit), there was no need for a re-estimation of these parameters during the Lander Delivery phase.

3.2. Re-optimization of Rosetta's and Philae's Reference Trajectories

Based on the latest estimated comet parameters, a re-optimization of Rosetta's trajectory and Philae's descent was performed. Some weeks before that, when analysing the candidate landing sites, a reference trajectory had already been designed to land on Agilkia while satisfying all mission constraints. This re-optimization simply had to adjust the Rosetta's and Philae's trajectories to the latest estimated dynamic models to meet the landing constraints.

This re-optimized trajectory defined the coordinates of the reference point in space where Rosetta should arrive at the beginning of the lander delivery sequence, i.e. right before the execution of the pre-delivery manoeuvre. The trajectory correction manoeuvres during the parking orbit were then optimized to target that reference point.

3.3. Navigation in the 30-km Parking Orbit

The SDP-2 manoeuvre (9.6 cm/s), executed on October 31st, inserted Rosetta in the 30-km parking orbit. A stochastic manoeuvre slot, SDP-SLOT-2 (0.5 cm/s), was scheduled on November 3rd to correct the accumulated navigation error. After that, the spacecraft was on track, closely following the reference trajectory prepared in advance.

The rationale of driving Rosetta to fly almost a full revolution around the comet in the 30-km parking orbit (2 weeks orbital period) was to arrive with the smallest possible navigation error to the reference point at the beginning of the lander delivery sequence. This way, it should always be possible to compensate small arrival position errors by small adjustments to the landing trajectory. Three stochastic manoeuvre slots (7, 3, and 1 day(s) before landing) were scheduled to correct for these navigation errors and retarget the trajectory to the reference point.

Thanks to the latest comet dynamic model estimated in the long arc, the navigation accuracy improved significantly compared to similar 30-km orbits flown in September during the Global Mapping phase. This allowed skipping the manoeuvres scheduled for -7 and -1 day(s), thus helping to simplify operations in such a busy period and improving the accuracy of the last orbit determination used to optimize and command the full landing sequence. Furthermore, the executed correction manoeuvre, 3 days before landing, required a very small ΔV: 0.3 cm/s.

Another factor influencing the navigation accuracy, although not as much as gravity, was the modelling of the coma drag. In the orbit determination process the drag due to the coma is modelled using the measurements of the ROSINA scientific instrument [11], but these data are only available for orbit reconstruction. For orbit prediction, an ESOC engineering coma model [12] is used. In each commanding cycle, an additional OD was run using the operational coma model to estimate a short-term scale factor that was subsequently used for the orbit prediction and trajectory optimization process.

3.4. Lander Delivery Commanding Cycle

The commands for the lander delivery sequence were prepared on November 11th. The Flight Dynamics operations started 24 hours before landing, once the latest navigation images were downloaded on ground. The main tasks performed in the FD cycle were: image processing to identify the landmarks [13]; orbit determination using the landmark observations and 2-way radiometric data [9]; orbiter and lander trajectory optimization; generation of the AOCS commands for the manoeuvres, the spacecraft attitude guidance, and the lander separation [14].

Two GO/NOGOs decision points were scheduled in the timeline depending on the result of the FD operations. The first one was, once the orbit determination and trajectory optimization were performed, to confirm that Rosetta was on the right path arriving not too far away from the reference target point where the pre-delivery manoeuvre was to be executed. The second one was to confirm that all the commands were generated, checked, and ready to be uplinked to the spacecraft.

The third decision point was on the Philae team side, depending on the results of the preparation activities that had to be executed on-board before separation. Even though not all activities functioned nominally (e.g. failure of the pressurization of the cold gas system) the lander was ready for separation and the go-ahead was given.

3.5. Pre-delivery Manoeuvre Assessment

The performance of the pre-delivery manoeuvre had a significant impact on the landing accuracy. Therefore, the fourth, and last, GO/NOGO decision for separation was based on the assessment of the accurate execution of the manoeuvre. This assessment had to be done with a very limited reaction time (15 min after manoeuvre end time received on ground) because all separation commands were already stored on-board the spacecraft but, in order to be executed, a confirmation command had to be sent from ground and received by the spacecraft before the sequence start time.

The assessment of the manoeuvre was based on the analysis of: the spacecraft's telemetry that was being received during the manoeuvre execution, such as thruster on-times and temperatures, performance of the attitude control subsystem; and radiometric tracking, 2-way Doppler measurements, taken by the ESA deep space antenna in New Norcia. The nominal manoeuvre ΔV was 83.58 cm/s and the angle between the thrust and the Earth directions was 114.9 degrees, thus the expected change in 2-way range-rate was 703.8 mm/s. Figure 4 shows the computed range-rate (1s count time) residuals of a so-called pass-through using 2 different orbit propagations: without modelling the manoeuvre (left); and modelling the manoeuvre's nominal acceleration profile (right). Represented time scale is UTC reception time on ground.

The manoeuvre was extremely accurate: it ended only ~3 seconds earlier than nominal, stopped by the accelerometers that had been carefully calibrated for this manoeuvre [14], and over-performed by only 0.15 % (1.2 mm/s). Consequently the GO for separation was given.

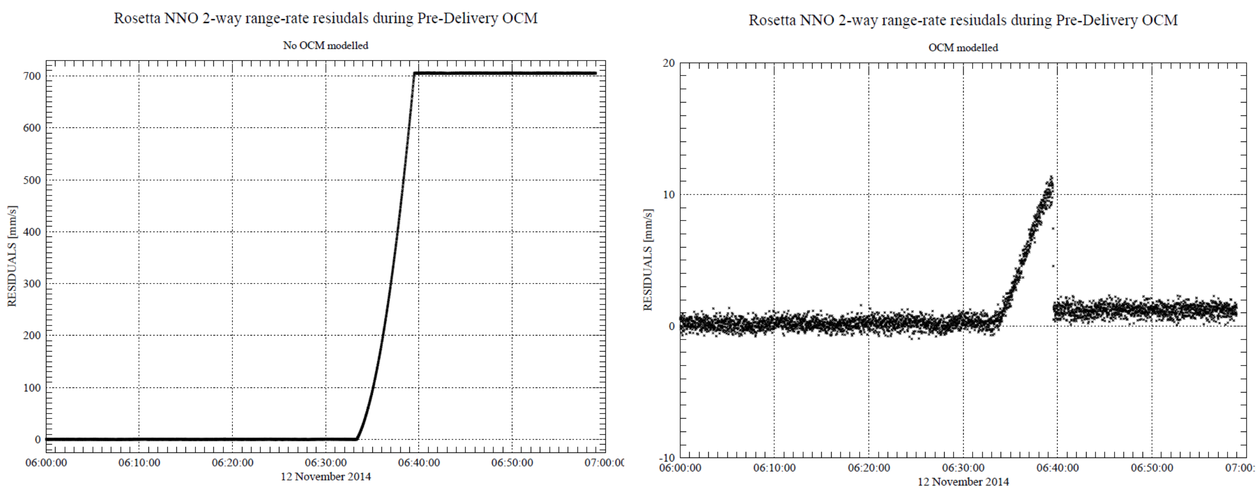

Figure 4. Range-rate residuals of the pre-delivery manoeuvre pass-through

3.6. Separation Assessment

The separation ΔV induced in Rosetta was also visible in the Doppler measurements, and using a similar approach as for the pre-delivery manoeuvre, the correct execution of the separation could also be confirmed with radiometric data.

Figure 5 shows the computed range-rate (1s count time) residuals of a pass-through of an orbit propagation without the separation modelled (time scale is UTC reception time on ground). The assessment showed that the separation was executed at the nominal time (within 1 second) and that the received ΔV on the orbiter was very close to nominal.

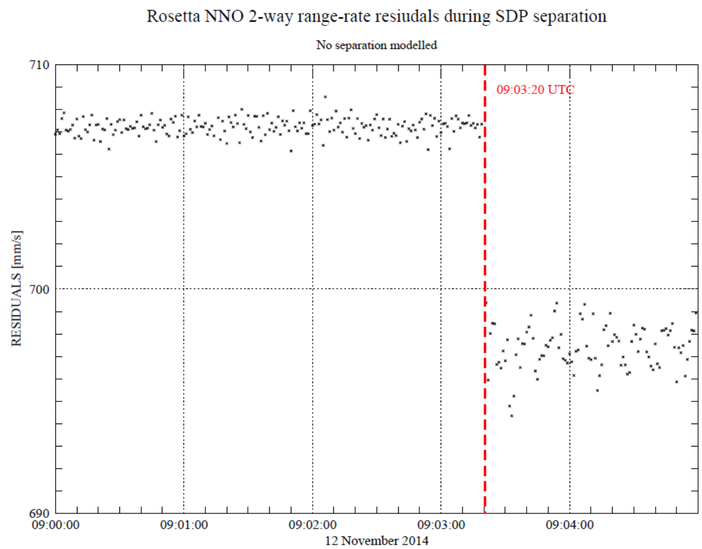

Figure 5. Range-rate residuals of pass-through around separation

3.7. Rosetta Trajectory Reconstruction

Once enough radiometric tracking data were accumulated and all images taken around lander delivery were downloaded to ground, a final reconstruction of Rosetta's trajectory around landing time was performed. The configuration was a short-arc OD using landmark and 2-way Doppler observations from November 9th to 20th.
The ODs including the time around November 13th required some additional effort to fit properly the data since at that time Rosetta was flying at a very low phase angle (Rosetta-Comet-Sun angle), exposing a significant fraction of its 64 m^2 solar array area to the incoming gas ejected from the comet nucleus. Figure 6 shows, in logarithmic scale, the computed accelerations for each modelled source: comet's central gravity, comet's gravity of 2nd degree spherical harmonics, solar radiation pressure, coma drag, and Sun's third-body gravity.

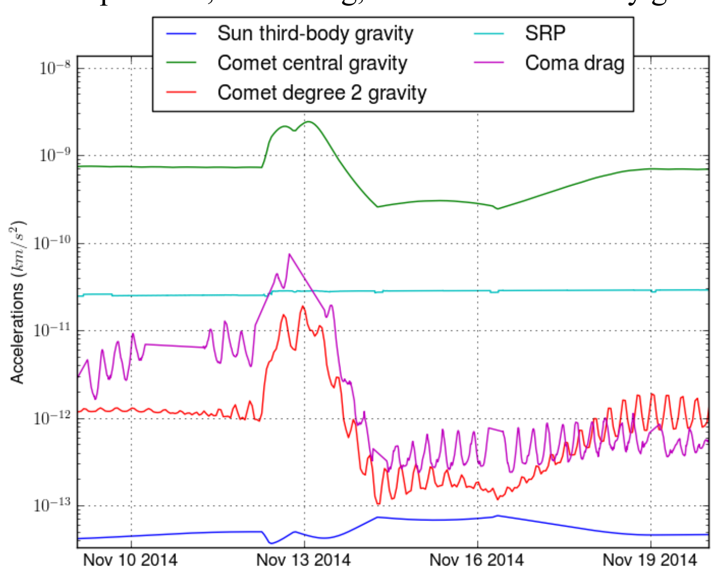

Figure 6. Rosetta accelerations around landing time

Figure 7 shows the 2-way range-rate residuals of the final reconstruction. In the zoomed-in view, a signature in the residuals can be observed from 11/12T17:00 to 11/13T09:00, corresponding to the time when Rosetta was flying at low phase angles. Most probably the signature in the residuals was produced by mis-modelled accelerations due to the coma drag, which in that period of time had to be based on the operational coma model since ROSINA instrument was switched-off. The operational coma model used at that time worked quite well to predict the average drag acceleration but was not meant to predict any short-term variation in the coma density.

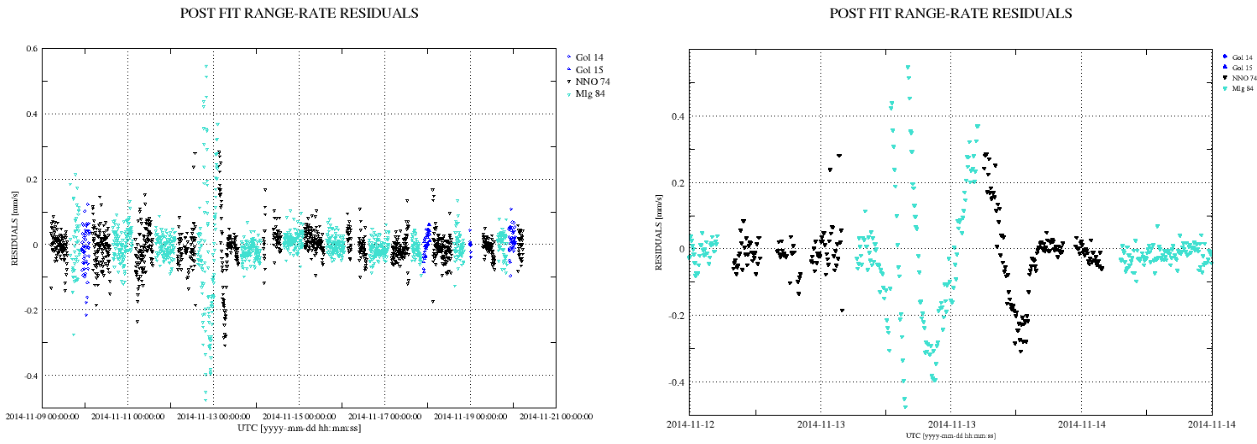

Figure 7. 2-way range-rate residuals of the final reconstruction (left); zoom around the time of lander delivery (right)

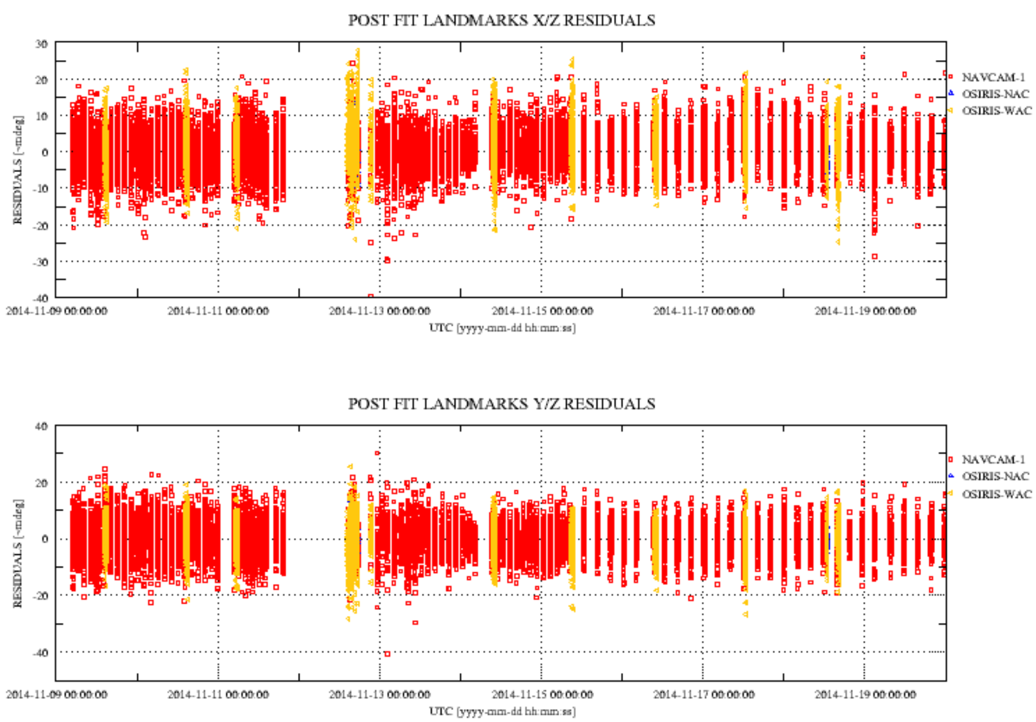

Figure 8. Landmark observation residuals

In the period of time from pre-delivery manoeuvre to 1 hour before landing, there were no optical images suitable for Rosetta navigation since the comet was out of the field of view of the on-board cameras, which were following the lander's trajectory. Because of this, the trajectory of Rosetta in that time interval is weekly observed and the reconstruction accuracy is somehow degraded, due to the uncertainties on the pre-delivery and post-delivery performance, and also on the separation ΔV induced in Rosetta. Figure 8 shows the landmark observation residuals in this OD, where the gap of images from 11/11T19:30 to 11/12T14:20 is clearly visible. This OD was also useful for estimating the alignment between OSIRIS-NAC and the NAVCAMs. OSIRIS-WAC images were being used during the whole comet phase but NAC images were very rarely used. Since the lander was also observed in NAC images it was beneficial for the lander OD to apply the estimated alignment from this Rosetta OD.

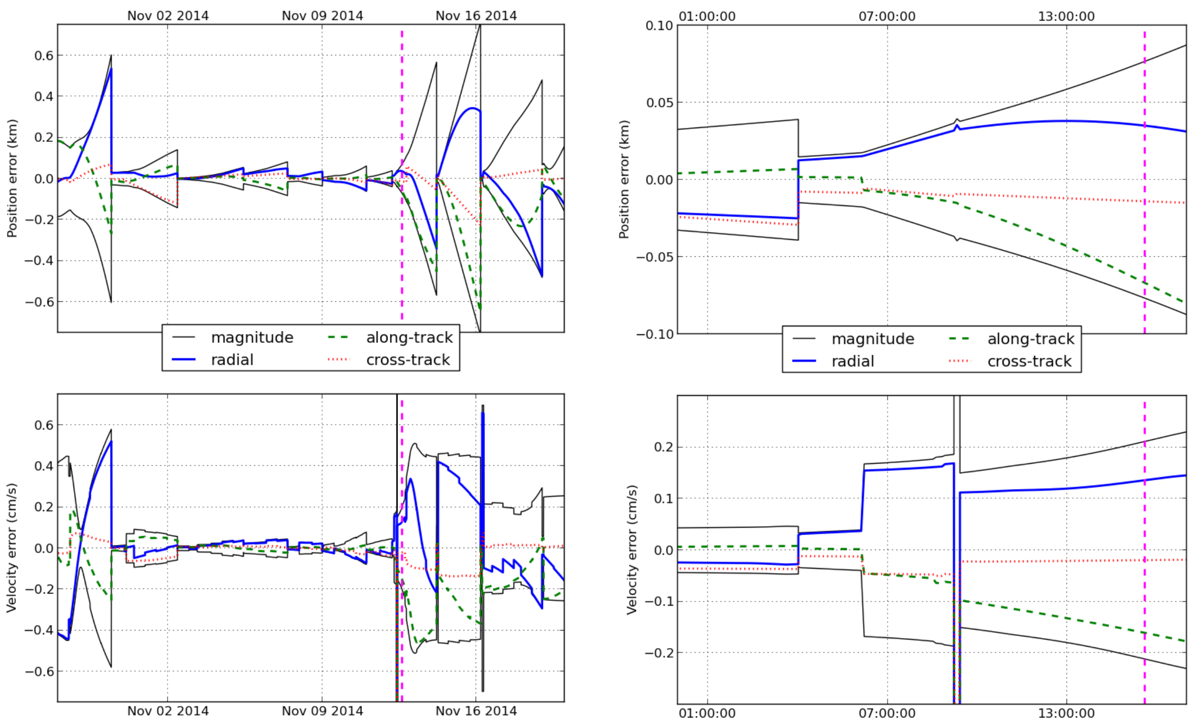

Figure 9. Orbit prediction errors during Lander Delivery phase (left) and zoom around landing time (right). Landing time is marked in dashed magenta

During operations, the navigation accuracy was assessed by comparing the reconstructed orbit with the predicted orbit that, during each planning cycle, was used to generate the FD commands. Given that the error in orbit reconstruction was order(s) of magnitude smaller than the orbit prediction errors then the difference predicted-reconstructed could be interpreted as the orbit prediction error. Figure 9 shows the orbit prediction errors, as difference in position and velocity of the predicted and reconstructed trajectories, given in magnitude and projected along radial, along-track and cross-track directions. Every time the error drops down corresponds to the moment in which the commands from a new planning cycle (based on a more recent OD) are executed on-board. Left side of the plot shows the prediction for the Lander Delivery and Relay Phases, while the right side shows a zoom in around landing time (marked in dashed magenta).

The commands for the lander delivery sequence started on November 12th at 04:00, this corresponds, in the right side plot, to the first drop in position error. From that time up to pre-delivery manoeuvre, the orbit prediction error is very stable, about 20 m. Due to the (small) mis-performance of the pre-delivery manoeuvre, the error in velocity increases, and the slope of the position error changes accordingly.

The Rosetta navigation error at separation time was 32 m in position and 1.7 mm/s in velocity and at landing time the position error was only 76 m. These figures reflect the excellent navigation accuracy that was achieved during this phase, which ultimately drove Philae to land so close to the target landing point.

4. Philae Trajectory Reconstruction

After the execution of the post-delivery manoeuvre, Rosetta performed a slew to point its antenna and scientific instruments to Philae. At that moment, the first packages of lander's telemetry were sent to ground and Rosetta started taking images with the navigation and the scientific cameras, while scanning around the nominal trajectory of the lander. In many of these images the lander appeared inside the camera's field of view.

The lander was also observed in 2 images after the first touch-down and rebound: one NAVCAM immediately after [15] and one OSIRIS-NAC image at 15:45 UTC [16]. In both images the shadow of the lander was also identified. Additionally, there were 2 later OSIRIS-WAC images (16:45 and 17:20) in which an object is observed flying above the crater. Although it cannot be easily confirmed, they are considered to be very likely actual observations of the lander. All this information was used to reconstruct the descent trajectory, the first touch-down point, the rebound, and the collision with the crater rim.

4.1. Orbit Determination Setup

The operational software for Rosetta OD was also used to perform the Philae OD. Since it was not designed to perform simultaneous determination of orbiter and lander trajectories, the process had to be split in two: (1) the normal Rosetta OD for orbit reconstruction (based on radiometric data and landmarks on the comet surface), (2) Philae OD in which Rosetta's trajectory is fixed to the result of the first step and Philae's trajectory is estimated using the lander observations.

The dynamic models for lander's acceleration computation during descent were based on the comet gravitational field (3×3 degree and order) and coma density values estimated in the Rosetta OD. The coma drag acceleration was computed using a constant cross-sectional area. The Solar radiation pressure was also included, using a flat plate model with cross-sectional area and absorption and reflectivity values provided by the lander manufacturer. Figure 10 shows the modelled accelerations in Philae trajectory propagation. The coma drag and the central gravity follow the same functional behaviour (proportional to the inverse of the square of the distance), being the drag about 2 orders of magnitude smaller than central gravity and directed radially away from the comet. The effect of the higher order gravity spherical harmonics (in the plot only 2nd degree are shown) become the dominant acceleration as the lander gets closer to 1-radius distance to the comet. However, the mis-modelling of the non-spherical gravity has a limited impact on the final touch-down position since it only starts to be significant in the very last stage of the descent.

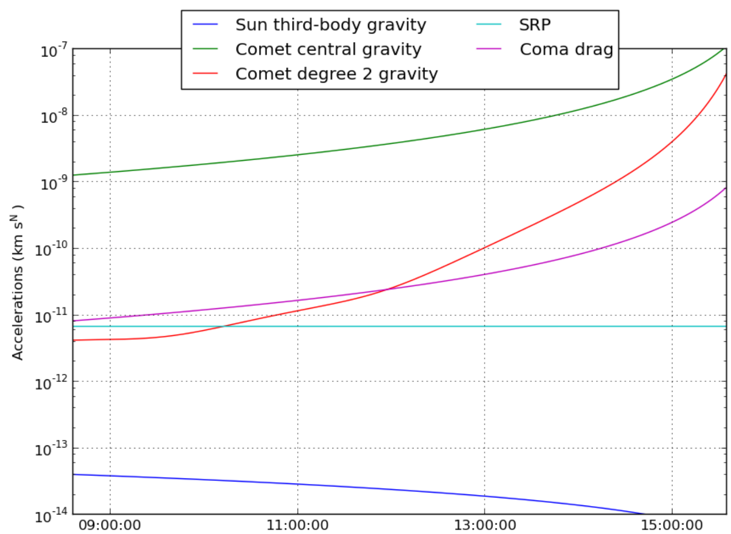

Figure 10. Philae accelerations during descent

In this OD setup, the lander is treated as the main spacecraft while Rosetta's trajectory is fixed, as a user-defined Solar system body. The optical observation modelling implemented in the operational SW supports only observations from the main spacecraft to Solar system bodies. Therefore, a trick was required in order to incorporate the lander observations in the OD. The approach followed was to derive the direction from Rosetta to the lander and then revert it so that the observation fed to the OD system would be equivalent to Philae having taken an image of Rosetta.

This simplified approach proved to work very accurately in the reconstruction of Philae's trajectory. However, it has the limitation that the information contained in the lander observations is not used to improve the knowledge of Rosetta's trajectory.

4.2. Descent Reconstruction

During the landing day, as images of the lander taken by Rosetta were being downloaded to ground, lander ODs were successively run with increasing number of observations. From the result of these ODs, it was possible to estimate the actual touch-down point by extrapolating the determined orbit and computing its intersection with the ESOC comet shape model [13].
This method provided very early an initial estimate of the touch-down point that later was proved to be very accurate, when the reconstruction of the touch-down point performed by SONC [17], based on ROLIS [18] images, was communicated to ESOC. The actual touch-down point was 118 metres away, mainly in south direction, from the target landing site, well within the 500 metres radius that was a priori considered as landing uncertainty.

Figure 11 shows the lander observation residuals of the final reconstruction performed, once all images were downloaded to ground and enough tracking data was accumulated to obtain a reliable reconstruction of Rosetta's trajectory. The fit is satisfactory although not brilliant, probably due to limitations of the dynamic modelling and Rosetta's trajectory reconstruction errors.

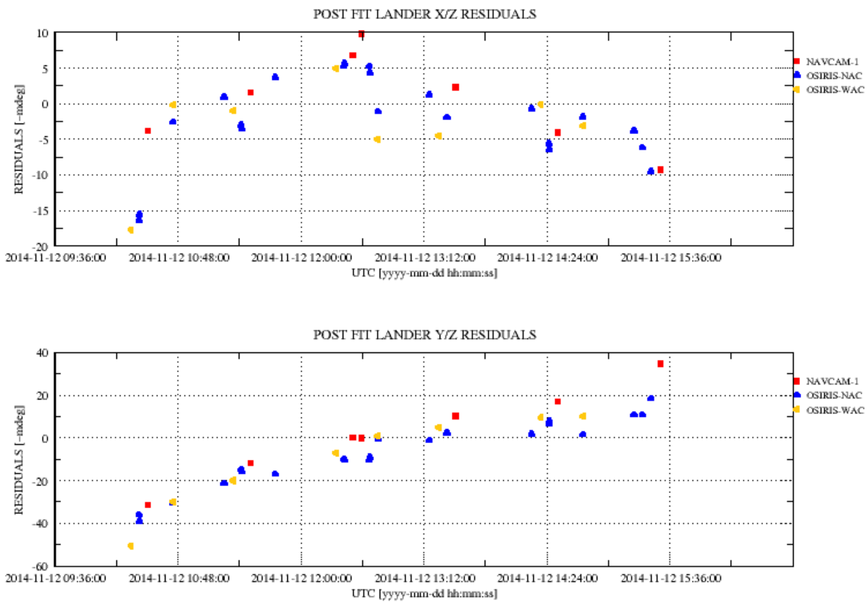

Figure 11. Lander OD optical residuals

The descent OD was configured to take the initial Philae's state vector (position and velocity) from the reconstructed Rosetta's state vector at separation time and adding to the velocity vector the nominal separation ΔV on the lander. In this setup only the velocity component immediately after separation was estimated while the position was fixed. By also estimating the initial position, the observations fit resulted to be much better, but the estimated shift in position at separation time was unrealistically big.

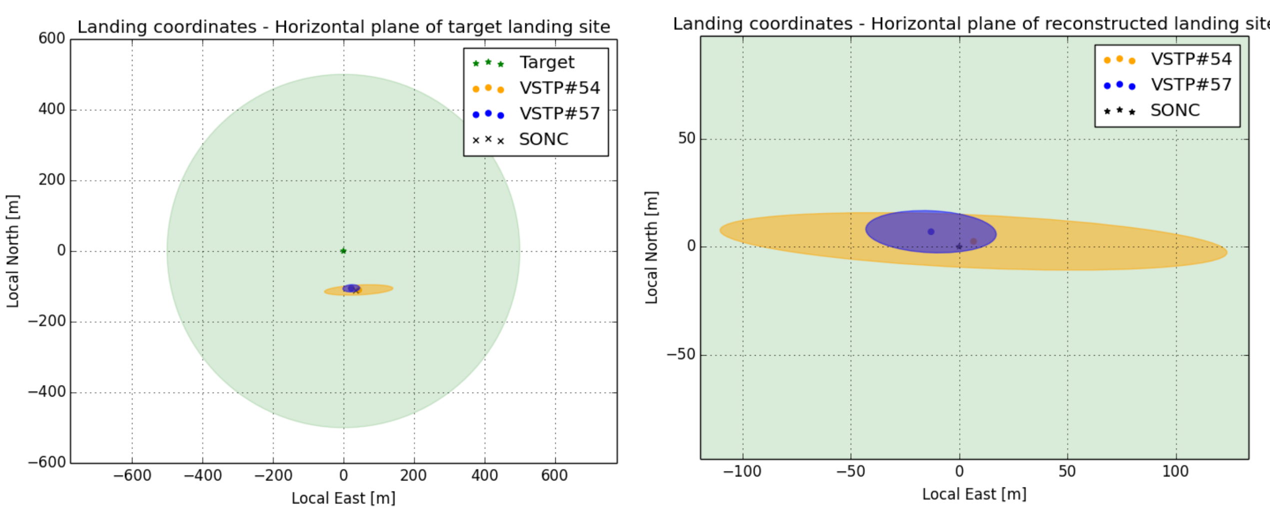

Figure 12. Reconstructed touch-down point and 3-sigma uncertainty ellipses

Figure 12 shows the estimated landing coordinates using the lander OD with corresponding 3-sigma uncertainties for 2 solutions: in yellow, the one obtained the landing day, which had less data and thus higher post-fit uncertainty, but was indeed very close to the actual touch-down point; in blue, the final reconstruction that was performed some days later. The black point marks the best estimate on the coordinates of the first touch-down point from SONC reconstruction.

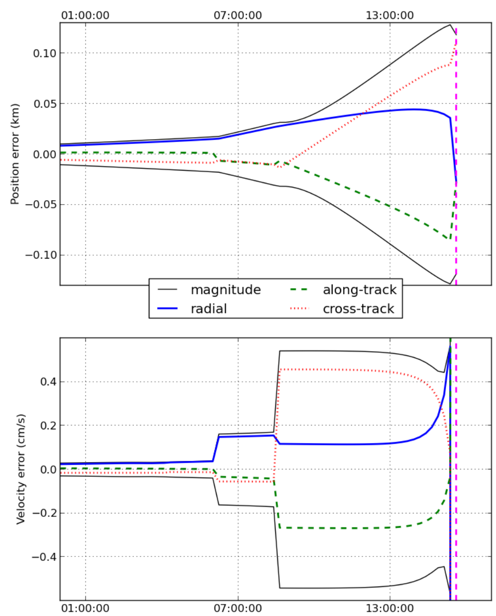

Figure 13. Philae's descent prediction errors

Figure 13 shows the prediction accuracy of trajectory of Philae starting on November 12th at 00:00, when it was still attached to Rosetta, until landing time (marked in dashed magenta). The difference in position at landing is consistent with the quoted 118 m of landing accuracy, as could not be otherwise, since the predicted trajectory was optimized to land in the target point.

4.4. Reconstruction of the Bouncing Trajectory above the Comet Surface

Since the final landing location of Philae was not known, it was worth to try to reconstruct its trajectory after the rebound at the first touch-down point. The motion of Philae after the first rebound was weakly observed: the lander appeared in only two images, in which, fortunately, both the lander and its shadow on the comet surface were found. The shadow observations were also introduced in the orbit determination process, allowing for a better estimation of the lander trajectory, since they helped to resolve the altitude at which Philae was flying over the surface.

Since the OD software was not prepared to model "shadow" observations, some creativity was required to find a way to introduce them as a supported observation type: the landmarks on the comet surface. From the shadow location in the image, the direction from Rosetta to the shadow was derived, and by intersecting that line with the ESOC shape model [13], the coordinates of the shadow in comet-fixed frame were computed. One landmark for each shadow was then defined with the resulting coordinates. Finally, a pseudo-landmark observation could be generated, at each image time tag, stating that the direction from Philae to its shadow should be parallel to the direction of the incoming Sun light.

Since Philae's trajectory after the rebound is quite sensitive to the dynamic model, the gravitational field expansion was augmented from 3x3 to 8x8 by adding the spherical harmonic coefficients derived from the latest comet shape model under the assumption of constant density.

In this OD the dynamics are not easy to model due to coma drag uncertainty and errors in the gravitational field so close to the comet surface. On top of that, Philae's trajectory was weakly observed (4 optical observations to determine 3 unknowns to model the rebound). Because of all this, the extrapolated trajectory after the OSIRIS image at 15:45 UTC is thought to have significant errors. However, from the result of this reconstruction it was possible to find out that: (1) after the rebound, Philae's flight path was directed towards the comet's south pole that was in permanent night at that time, and (2) the extrapolated Philae's trajectory was intersecting with the rim of the big crater next to Agilkia. This led to the conclusion that, very likely, Philae had collided with the crater rim, at a time around 16:25 UTC, changing its trajectory and preventing it from going further towards the comet south pole, where the illumination conditions would not be consistent with the solar panel telemetry received from the lander. This hypothesis was later confirmed by the lander team based on solar power and magnetometer readings, concluding that a collision event happened at 16:20 UTC.

Another Philae OD was run taking the lander's position from the previous one at the time of the collision with the crater rim and estimating the lander's velocity after the collision by using the 2 WAC images at 16:45 and 17:20 with candidate observations of the lander. By intersecting, again, the resulting trajectory with the shape model, the end time of the reconstructed trajectory was computed.

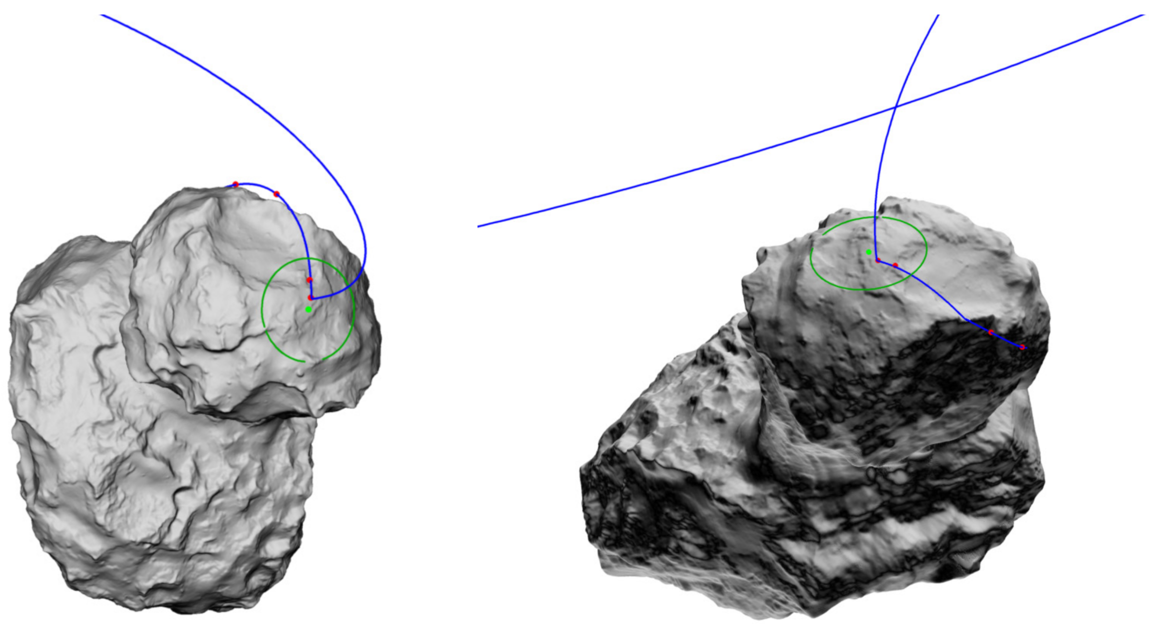

Figure 14. Views of reconstructed Philae's bouncing trajectory in comet-fixed-frame

Figure 14 shows the resulting comet-fixed frame reconstructed trajectory which, although it may have significant errors, provides a representative view of the path flown by Philae. The green dot represents the target landing site, and the green circle the 500 m a-priori landing uncertainty. The red dots represent the NAVCAM and NAC lander observations after the first touch-down and the two WAC images with the candidate lander.

The final OD setup was as follows: the initial Philae's position at separation time was fixed to the corresponding reconstructed position of Rosetta at separation; the position at first touch-down time was fixed to the best estimate available; the first rebound was modelled as an estimated impulsive ΔV at 15:34:06 UTC; the collision with the crater rim another estimated ΔV at 16:26 (the time when the determined trajectory collided with the crater rim). In this reconstruction, the last "hop" of ~7 min duration, deduced from the lander's telemetry [6], was not modelled, since no optical images are available for that time period.

Even though there are big uncertainties in the extrapolation of the trajectory after the NAC image at 15:45, the trajectory before that time is considered to be known accurately enough. This allows to perform a reasonable reconstruction of Philae's velocity with respect to the surface before and after the first touch-down, which expressed in local (East, North, Up) frame, were: (2.0, -20.7, -99.0) cm/s of incoming velocity and (21.3, -23.5, 7.2) cm/s of outgoing velocity. These figures reflect the good job performed by the landing gear to absorb a significant part of Philae's kinetic energy at touch-down.

The incoming velocity formed an angle of 12 degrees with respect to the local vertical direction, which comes from the fact that the local vertical of the actual touch-down point and the local vertical of the target landing point form an angle of 12 degrees. Comparing the incoming inertial velocity of Philae with the designed inertial velocity shows that the achieved Philae's velocity direction was very accurate: less than 0.5 degrees apart.

5. Possible Enhancements of the Trajectory Reconstruction

The operational ESOC orbit determination software was not initially foreseen to be used to perform Philae OD, or even less to ingest shadow observations. With some creativity and modelling simplifications, it was possible to meet that need without having to upgrade the operational software. Even though the results were very satisfactory, the process had certain limitations that could be overcome by a simultaneous determination of Rosetta and Philae's trajectory, and even comet attitude, using all available observations:

- Since the OD process had to be split in two steps (Rosetta OD and Philae OD) any error in Rosetta's orbit coming from the first OD (which indeed was weakly observed between pre-delivery manoeuvre to the first lander's descent image with the comet in the background) could not be corrected by the information provided by the lander observations. The same happened with the initial position of the lander at separation time.
- The separation ΔV on both Rosetta and Philae were modelled in each OD independently. However, in reality they are connected by the law of conservation of linear momentum, which could be modelled as a linear constraint in a combined OD.

- To incorporate the shadow observations in the Philae OD, an intermediate step was required to compute the intersection of the comet shape model with the direction from Rosetta to the shadow, in order to obtain the shadow coordinates in comet fixed frame. Errors in Rosetta's position at that time translate to errors in the shadow coordinates, which ultimately translate to bigger errors in corresponding Philae's position. This issue would be resolved in a combined Rosetta and Philae OD.
- CONSERT [19] measurements of the range between Rosetta and Philae that were taken during descent and after final touchdown could be incorporated in a combined OD.
- The coordinates and the time of the first touch-down are very well known, thanks to Philae's telemetry, the reconstruction made using ROLIS images during descent, and also from the Rosetta's images of the footprints of the lander's legs on the comet surface. This information could be used as a constraint in a combined OD and, consequently, translated to an improvement of the estimation of the Rosetta's orbit.

Additionally, other improvements could be performed in the lander dynamics modelling, since there are significant uncertainties in the gravitational field modelling with Philae flying so close to the comet surface. The 8x8 gravitational field expansion was derived from the, at that time, latest shape model, which had not resolved the comet's south pole since a big part of the southern hemisphere had been in permanent night. From May 2015 onwards, the comet season changed and the south pole was fully illuminated, allowing for a complete resolution of the comet shape. Using this fully-resolved shape model would definitely improve the accuracy of the modelling of the comet's gravity.

6. Conclusions

This paper has presented the navigation of Rosetta during the first-ever soft landing on a comet, described the trajectory flown during the Lander Delivery phase, the achieved navigation results and landing accuracy, as well as the performed reconstruction of Philae's descent, touch-down point, rebound, and the subsequent flight over the comet surface.

Although very challenging and demanding, Rosetta navigation during Lander Delivery phase was considered a success, since all operations could be conducted nominally and very accurately; and the first landing point was only 118 metres away from the target landing site, well within the 500 metres radius that was a priori considered as landing uncertainty.

Additional, and unforeseen, effort was spent in the reconstruction of Philae's bouncing trajectory, which helped in the understanding of the conditions of the descent, rebounds and collision, and confirmed the estimated region where the Philae finally landed.

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