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

Pablo Muñoz[1], Frank Budnik[2], Vicente Companys[2], Bernard Godard[3], Carlos M. Casas[1], Trevor Morley[3], and Vishnu Janarthanan[4]

[1] *GMV, located at ESOC*. Email: Pablo.Munoz@esa.int, cmcasas@gmv.com*
[2] *European Space Agency, located at ESOC* Email: <firstname>.<lastname>@esa.int*
[3] *Telespazio VEGA GmbH, located at ESOC*. Email: <firstname>.<lastname>@esa.int*
[4] *Terma GmbH, located at ESOC*. Email: <firstname>.<lastname>@esa.int*

* *Robert-Bosch-Strasse 5, 64293 Darmstadt, Germany. +49 6151 900*

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

ABSTRACT

After ten years of interplanetary flight, ESA's Rosetta spacecraft arrived to its final destination, the comet 67P/Churyumov-Gerasimenko, on 6th August 2014. The first three months of operations around the comet were dedicated to characterize its shape, surface, mass, gravity field, rotational state and coma density distribution, in order to improve the navigation accuracy as well as to identify candidate landing sites. All this knowledge had to be progressively acquired in flight, allowing for flying at closer distances to the comet. In October, the spacecraft was flying as close as a 10 km orbit from the centre of the comet. At that distance, the most accurate determination of the comet physical properties was obtained, which led to a significant improvement of the navigation accuracy, especially due to the refinement of the estimated comet gravity field and the location of its centre of mass. Additionally, at that time, the suitability of the prime landing site, named Agilkia, was ultimately confirmed, giving way for the transition to the next mission phase: the delivery of the Philae lander.

The landing date was set to 12th November 2014. Two weeks before that, the spacecraft was inserted in a 30 km orbit, in a plane tilted 20 degrees with respect to the day-night terminator plane. The trajectory was designed such that, after completing almost one orbital revolution, the spacecraft would arrive to the selected position at the time of the beginning of the lander delivery sequence. In order to correct for navigation errors, three stochastic manoeuvre slots were scheduled to 7, 3 and 1 days before landing. Thanks to the latest estimation of the comet physical properties, the achieved navigation accuracy was good enough to skip the manoeuvres 7 days and 1 day before landing. This helped to simplify operations in such a busy period and improved the accuracy of the orbit determination that was used to optimize and command the full landing sequence.

The Flight Dynamics operations to prepare the lander delivery sequence started 24 hours before landing, once the latest navigation images were downloaded on ground. It consisted in: image processing to identify the landmarks; orbit determination using the landmark observations and 2-way radiometric data; orbiter and lander trajectory optimization; generation of the AOCS commands for the manoeuvres, the spacecraft attitude profile, and the lander separation.

The lander delivery sequence started 9.5 hours before landing with the execution of the pre-delivery manoeuvre. With a ΔV of 84 cm/s, the manoeuvre drove the spacecraft to a hyperbolic trajectory with 5 km pericentre distance. 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 separated from Rosetta at a comet distance of 23 km. The separation mechanism introduced a ΔV of 17.4 cm/s on the lander, directing its trajectory towards the target point on the surface of the comet. After separation, Rosetta executed the post-delivery manoeuvre to avoid passing by the minimum distance of 5 km and to ensure visibility and communications with the lander during descent. 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 were later used to perform the orbit determination of the lander trajectory.

Philae telemetry, which was received on ground via Rosetta, confirmed that landing occurred at 15:34:04 (UTC, on-board time). Philae was equipped with a cold gas thruster, two harpoons, and screws in its legs that, ideally, would have anchored it to the comet surface. 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 gravity. Philae continued an additional 2-hour flight, in which it collided with a crater rim, it had another smaller rebound, until it finally landed on the comet surface where it successfully executed its primary science mission.

Using the observations of Philae in the images taken by the optical cameras on-board Rosetta, it was possible to reconstruct the descent trajectory, the first touch-down point and the rebound. 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 detected. The shadow observations were also introduced in the orbit determination process, allowing for a better estimation of the lander trajectory. This reconstruction showed that, very likely, Philae had collided with the rim of the big crater next to Agilkia, changing its trajectory and preventing it from going further towards the comet south pole, where the illumination conditions were worse at that time.

Rosetta navigation during lander delivery phase was considered a success, since all operations could be conducted nominally 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.

This paper presents the 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 descent, touch-down point, rebound, and the subsequent flight over the comet surface.