ROSETTA NAVIGATION FROM REACTIVATION UNTIL ARRIVAL AT COMET 67P/CHURYUMOV-GERASIMENKO

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ABSTRACT

After 31 months in hibernation, Rosetta was successfully reactivated on 20 January 2014 when it was 5.3 au from the Earth, 4.5 au from the Sun and 9.2 million km from its target destination, comet 67P/Churyumov-Gerasimenko (67P/C-G). As expected, there was no problem of sufficiently accurate pointing of the ground antenna to receive the spacecraft signal because the predicted uncertainty was only a tiny fraction of the 3dB beam-width.

During the following days the spacecraft's orbit was determined using conventional two-way Doppler and range measurements acquired by both ESA and NASA/DSN deep space antennas. As a precaution, the ranging code length was increased to raise the ambiguity factor to well above the default of 4626 km in case the predicted distance from Earth was wrong by more than half this value. It turned out that the prediction made in June 2011 for the spacecraft's position was in error by just 500 km and its velocity differed from the prediction by 0.5 m/s.

At that time, Rosetta's velocity relative to the comet was 800 m/s and aligned very close to the target's predicted direction. The comet's predicted trajectory was based on a long-arc orbit solution that used only ground-based astrometric data from 1988 until 05 October 2013. During the following winter the solar elongation was too low for acquiring observations. On the assumption that the maximum comet activity occurred at perihelion, the estimate for the transverse component of the standard non-gravitational force model was positive, indicating that the comet's rotation was prograde (that was later confirmed during the close approach phase).

More astrometric data were acquired, starting on 28 February 2014. Including them in the orbit determination led to a change in the comet's estimated position of 1200 km but with a formal 1σ uncertainty almost as large as the change. This was considered to be an optimistic evaluation mainly because the data had to be reduced using a star catalogue known to suffer from significant zonal biases but also because of limitations in accurately modelling the non-gravitational forces.

To reduce the relative velocity to less than 1 m/s at arrival at the comet, the plan was a series of 10 individual manoeuvres. The first was foreseen to be a test burn of 20 m/s on 07 May, followed two weeks later by the largest single manoeuvre of 290 m/s, and then successively smaller manoeuvres.

The two identical on-board navigation cameras (NAVCAMs) can detect objects down to visual magnitude 12. The comet was expected to reach this brightness in early May but even without detection and thus no optical navigation, the first two manoeuvres would have been performed. However, the science payload OSIRIS Narrow Angle Camera (NAC) is much more sensitive and the OSIRIS team agreed to provide their images for navigation purposes. The NAC field-of-view (FOV) is 2.2° x 2.2°, less

than half that of the NAVCAMs, but even with the most pessimistic assumptions on possible errors in the comet's relative direction, it was considered certain that it would appear in the FOV.

On 24 March, when still 4.9 million km from the comet, an object was identified in NAC images 22 millidegrees from the expected location and moving across the sky with the expected speed and direction of the comet. Including the reduced data from the first six images changed the comet's estimated relative position by 2020 km. The first NAVCAM images with comet detection were acquired on 08 May at a relative distance of 1.8 million km. Except towards the end of the approach phase, the comet appeared as a point-like object and the optical navigation, using reduced data from both cameras, was made in the same way as for the fly-bys of asteroids Šteins and Lutetia (presented at ISSFD21 & 23).

There were two main drivers for the design of the manoeuvre strategy. One was robustness: the need to have a sufficient time margin if, for any reason, a manoeuvre could not be performed at the planned time so that it could still be executed well before flying past the comet. For the first main manoeuvre, the margin was 14 days and then, with decreasing relative velocity, reduced in steps down to 3 days for the final rendezvous manoeuvre. The other driver was to aim continuously not directly at the comet but with an off-set so that its apparent motion against the stellar background would provide information on the separation distance. Initially, this off-set was 50000 km and was reduced in steps down to 200 km for the penultimate manoeuvre. This meant that the relative trajectory had a very slight spiral appearance. The penalty for the required extra propellant was insignificant.

To achieve the best possible accuracy for the orbit and the manoeuvre calibrations, starting on 28 April the radiometric data were augmented with differential one-way range (DOR) measurements acquired predominantly by the ESA deep space stations on the Cebreros-New Norcia and Cebreros-Malargüe baselines. In total, these measurements were reduced to 57 delta-DOR data points.

After each manoeuvre the Doppler data were processed to obtain a preliminary performance estimate. On several occasions, after the attitude slew back to pointing the payload instruments towards the comet, the data showed indications of outgassing causing an accumulative delta-V of up to a few mm/s. Also, unexpected variations in the reaction wheel speeds were observed. These findings were confirmed by the ROSINA experiment that analyses the gas environment at the spacecraft. It is believed that products of combustion adhered to the -Z-face of the spacecraft, where the thrusters are located, and then were blown away when the face became illuminated by the Sun after each post-manoeuvre slew.

After 06 June, only the NAVCAM provided images for optical navigation. In early July the comet began appearing as an extended object. As it grew in size, the scatter in the data residuals increased and some trends developed due to limitations in identifying the true centre of the comet when observing at a slowly varying solar phase angle above 30°. For example, on 31 July, at 1284 km distance, 5 km (roughly the longest axis of the comet) was equivalent to an angular size of 0.223° or almost 45 pixels of the NAVCAM. The scatter in the optical right ascension residuals was then up to 4 pixels and in the declination residuals up to 2 pixels.

This modelling problem had no influence on the safe arrival of the spacecraft at the comet and the performance of all the manoeuvres was good. The last manoeuvre of 0.89 m/s on 06 August 2014 inserted the spacecraft into a hyperbolic trajectory around the comet with a pericentre distance of 80 km. The initial characterisation of 67P/C-G's physical characteristics then began with emphasis on determining its gravitational constant, rotation period and spin axis direction.