PREPARATIONS AND STRATEGY FOR NAVIGATION DURING ROSETTA COMET PHASE

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Abstract: *Rosetta entered in hibernation mode in June 2011. During 31 months it will fly silently towards its encounter with the comet 67P/Churyumov-Gerasimenko. The spacecraft is set to reactivate again in January 2014, and four months later the Rosetta Comet Phase will formally start. During this phase Rosetta will detect, approach and fly around the comet to study its properties. It will deliver the lander module, Philae, to touch down the comet's surface. And finally, will monitor the increasing activity of the comet as it approaches the Sun. The navigation around the comet is quite challenging due to the limited a priori knowledge on the comet kinematics and dynamical properties. This information need to be acquired during the navigation process itself in order to progressively improve the navigation accuracy. Some method of measuring the relative position of the spacecraft with respect to the comet is required. For this purpose, the optical cameras on-board Rosetta will be used to take images of the comet from which the directions to the comet's centre or to recognizable features (landmarks) on the comet's surface will be deduced. It will be the first time that optical navigation with landmarks is used in ESA spacecraft operations. This paper presents an overview of the navigation strategy and the preparations that have been performed by the ESOC Flight Dynamics team for the Rosetta Comet Phase, which mainly include the development of a new orbit determination software and the design and navigation analysis of the trajectories for each mission subphase.*

Keywords: *Rosetta, optical navigation, comet orbit and attitude determination, trajectory design, 67P/Churyumov-Gerasimenko.*

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 the 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 and Mars) in order to obtain the required velocity to reach the comet. During its long journey, Rosetta had close encounters (fly-bys) with 2 asteroids: (2867) Šteins and (21) Lutetia.

In January 2011, the first series of rendezvous manoeuvres (RDVM#1) were executed, ending with an additional trim manoeuvre on February 10th. With a total ΔV of 788 m/s, the trajectory was successfully adjusted to rendezvous the comet in August 2014. Meanwhile, the heliocentric distance of Rosetta kept increasing such that less and less power was received in the solar arrays. To reduce its power consumption to the minimum, the spacecraft entered hibernation mode on 8th June 2011, switching off almost all its systems, except the main computer and several heaters. It will be flying, without communication with Earth, on its way to meet the comet, until 20th January 2014, when the spacecraft is set to reactivate again. Four months later, the Rosetta Comet Phase will formally start with the execution of the second series of rendezvous manoeuvres (RDVM#2) while approaching the comet. After encountering the comet in August 2014, Rosetta will fly around it to study its characteristics, will release the lander to touch down its surface, and will escort the comet in its perihelion passage to study its increasing activity. Figure 1 illustrates the trajectory of Rosetta (in ecliptic projection) from Lutetia fly-by in July 2010 up to comet encounter in August 2014, including the hibernation period.

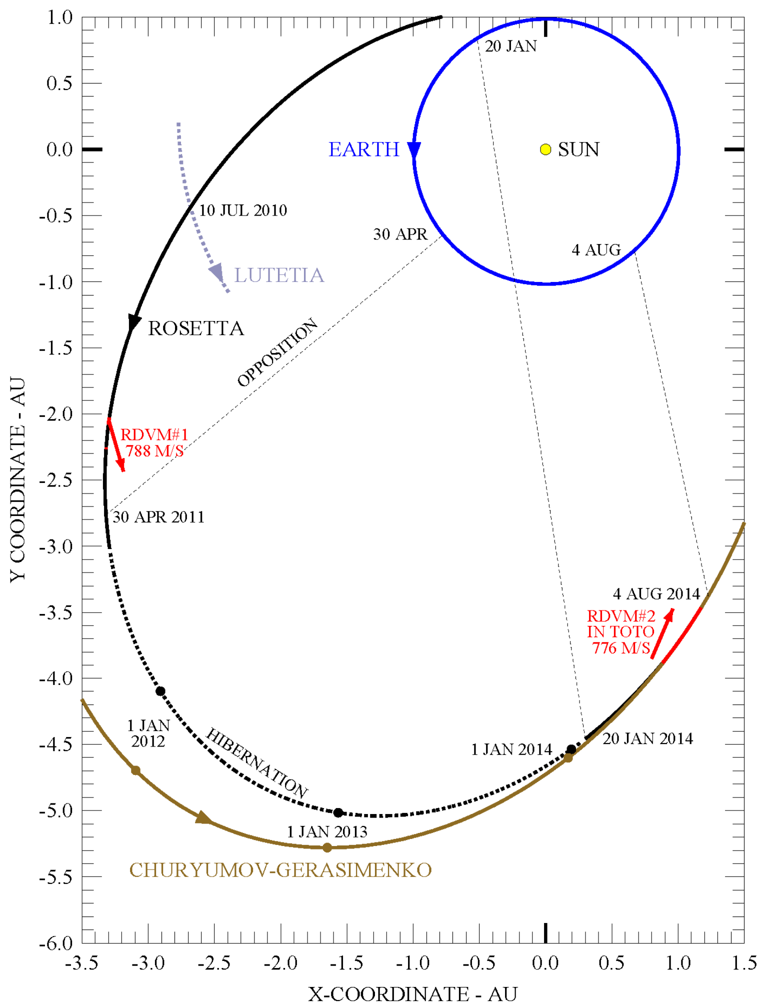

Figure 1. Rosetta trajectory from Lutetia fly-by to comet encounter

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 (Tab. 1) that can be used for relative navigation: 2 redundant navigation cameras (NAVCAMs) and 2 cameras from OSIRIS scientific instrument [1] (NAC and WAC, respectively Narrow Angle Camera and Wide Angle Camera).

Table 1. Characteristics of the optical cameras on-board Rosetta

Camera	Number of pixels in CCD	Pixel angular size [mdeg]	Total field of view [deg]	Signal resolution [bits/pixel]	Reference magnitude for detection
NAVCAMs	1024 x 1024	5.0	5 x 5	12	11
OSIRIS-NAC	2048 x 2048	1.1	2.2 x 2.2	16	15
OSIRIS-WAC	2048 x 2048	5.8	11.3 x 12.1	16	11-12

1.3. Comet 67P/Churyumov-Gerasimenko

The comet 67P/Churyumov-Gerasimenko (Tab. 2), final target of Rosetta, was discovered in 1969, by Klim Churyumov when he was examining images of comet 32P/Comas Solá taken by Svetlana Gerasimenko. Before 1840, the comet perihelion distance was 4 AU and it was completely unobservable from Earth. That year a close encounter with Jupiter changed its orbit, lowering the perihelion to 3 AU. In 1959, another Jupiter encounter reduced the perihelion again, resulting in the current orbit of the comet.

Table 2. Characteristics of the comet 67P/Churyumov-Gerasimenko

Perihelion distance	Aphelion distance	Orbit inclination	Orbit eccentricity	Orbital period	Nucleus' diameter	Rotation period
1.24 AU	5.54 AU	7.12°	0.632	6.57 years	3 – 5 km	~ 12 hours

1.4. Rosetta Navigation during Comet Phase

The navigation of Rosetta around the comet is quite challenging due to the uncertain *a priori* knowledge on comet kinematics and dynamical properties: mass, size and shape, moment of inertia, orientation and angular rates, gravitational field, and outgassing properties. All this information must be acquired during the navigation process itself, so that the navigation accuracy is progressively improved. An accurate navigation is a prerequisite to safely fly closer to the comet, to point scientific instruments to regions of interest on the comet's surface and to provide an accurate descent trajectory for the lander delivery.

Radiometric tracking from ground stations on Earth (range, Doppler, ΔDOR) provides very accurate information on spacecraft's trajectory with respect to solar system barycentre. However, these observations alone are insufficient to obtain an accurate estimate of spacecraft's trajectory relative to the comet, due to the large *a priori* uncertainty in the comet's trajectory. Therefore, some method of measuring the relative state is required to improve the relative navigation performance. For this purpose, on-board optical cameras will be used to take images of the comet to deduce the directions from Rosetta to comet's centre or to any recognizable feature, landmark, on the comet's surface. The first technique has already been successfully used for the Šteins [2] and Lutetia fly-bys [3], while the navigation with landmarks has never been used before in ESA spacecraft operations.

At the beginning of the Comet Phase, the first navigation task is to detect the comet with the optical cameras. Images of the region of the sky where the comet is expected to be will be taken. Each image will be processed on ground to remove the star background trying to find remaining visible points likely to be comet. Once the comet is found, its inertial direction from the spacecraft can be accurately deduced from the image, using the directions to the known stars in the image background. The comet's magnitude as seen from the spacecraft decreases in time because the relative distance and the comet solar phase angle decrease. In April 2014, the solar arrays will generate enough power to use the OSIRIS-NAC, which could then detect the comet. Due to their less sensitivity, the detection with the NAVCAMs is expected later, in May. Figure 2 shows the expected comet directions from Rosetta in early May with the star background taken from the PPMXL catalogue [4]. Comet observations from Rosetta are essential to determine the relative trajectory, so that the rendezvous manoeuvres can adjust the trajectory towards the comet. Once the spacecraft is sufficiently close to the comet to identify landmarks on the surface, this observation type will become the primary navigation data source.

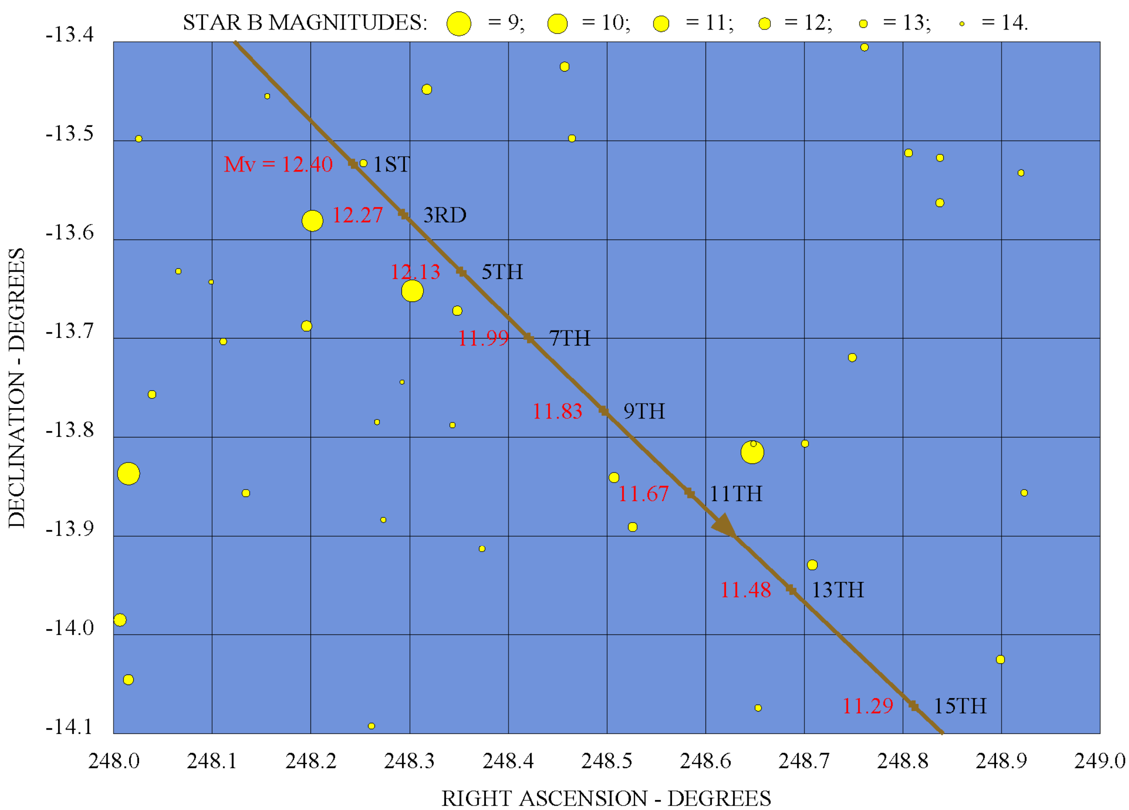

Figure 2. Comet directions from Rosetta with star background in early May

2. Orbit Determination Software

During the previous phases of Rosetta mission, the orbit determination was performed using three separate computer programs of the ESOC's interplanetary orbit determination system [5]: i) spacecraft orbit determination using radiometric data only; ii) asteroid or comet orbit determination using astrometric data only; iii) spacecraft-body relative state estimation using optical measurements of the direction from spacecraft to body centre, taking as input the OD solutions (estimated parameters and covariance information) from the two previous programs.

In preparations of the Rosetta Comet Phase, a new orbit determination program has been developed to perform simultaneous determination of spacecraft orbit relative to the comet, comet orbit relative to the solar system barycentre, comet orientation and angular rates and estimation of other spacecraft and comet dynamic parameters, using radiometric tracking and optical measurements of directions from spacecraft to the comet centre and landmarks on the comet's surface. Moreover, this new program will support all upcoming ESA deep space missions. The main new functionalities implemented in the new software are:

- Comet attitude propagation and estimation: integration of rigid body attitude dynamics and variational equations.
- Comet orbit propagation and estimation: reuse of spacecraft propagator adding models for comet non gravitational accelerations.
- Spacecraft orbit propagation and estimation: possibility of choosing the comet as centre of orbit integration. Addition of acceleration models due to comet's environment gravitational field and coma drag.
- Observations modelling: implementation of a model for the directions from the spacecraft to landmarks.

2.1. Orbit Determination Program Design

In previous ESOC's interplanetary orbit determination program, only the spacecraft orbit state is propagated, integrating the equations of motion and variational equations. The product of this propagation is the spacecraft state vector (position and velocity, and optionally acceleration and jerk) at any instant of time; and the partial derivatives of this state vector with respect to the state at the initial epoch and any dynamic parameter affecting the spacecraft trajectory. For the new software, it was necessary to extend the propagated state to contain also the comet orbit and attitude states (position, velocity, attitude quaternion and angular rates). One global propagator could have been written to integrate at the same time the 3 states, with its corresponding variational equations. Instead of that, the approach followed was to decouple the 3 propagations, under the assumptions that the trajectory of Rosetta does not affect the orbit and attitude of the comet, and also, that the comet attitude dynamics are independent of (small) changes in the comet trajectory. Using these assumptions, the logic of the orbit determination program can be summarised as follows:

1. Propagation of comet attitude.
2. Propagation of comet orbit (could be affected by propagated comet attitude).
3. Propagation of Rosetta orbit (affected by propagated comet attitude and orbit).
4. For each observation:
    - 4.1. Modelling of the observation.
    - 4.2. Computation of residuals and weighted observation equation.
    - 4.3. Accumulation of observation equation in estimator information array.
5. Computation of updates for the estimated parameters.
6. Back to point 1, until convergence is achieved.

The main advantages of this split are:

- The propagations can be performed by different integrator implementations and/or using different steering parameters, such as the time step. Using an adapted time step for each propagation makes the whole process more efficient in execution time.

- The estimation epochs for spacecraft orbit, comet orbit, and comet attitude can be set independently.
- Each propagator implementation is simpler, and the already existing and operationally tested orbit propagator can be reused for both spacecraft and comet orbit propagation.

2.2. Comet Attitude Propagation and Estimation

The problem of comet attitude propagation consists in, given an initial attitude state at a reference epoch, compute the attitude evolution during a defined time interval by integrating the rigid body equations of motion. At any time, the attitude state is expressed by a unit quaternion ($Q = q_1\mathbf{i} + q_2\mathbf{j} + q_3\mathbf{k} + q_4$) uniquely identifying the comet-fixed frame orientation in inertial frame and the angular rates Ω around each comet axis. Assuming that the comet inertia matrix J is time independent, the attitude dynamics equations is:

$$\begin{aligned} \dot{Q} &= \frac{1}{2} Q * \widetilde{\Omega} \\ \dot{\Omega} &= J^{-1}(T - \Omega \times J\Omega) \end{aligned} \tag{1}$$

where T is the sum of all torques affecting the comet, and $\widetilde{\Omega} = \Omega_1\mathbf{i} + \Omega_2\mathbf{j} + \Omega_3\mathbf{k}$ is the angular rate vector in quaternion form.

For estimation of dynamic parameters, it is required to keep track of the contribution of each dynamic parameter on the propagated attitude state, i.e. the partial derivatives of the attitude state with respect to any dynamic parameter, including the initial state at estimation epoch. This is achieved by integrating also the variational equations together with the rigid body equations. The numeric integration scheme used is an eight order Runge-Kutta with constant time step.

The parameter estimation algorithm (batch SRIF [6]) has been reused from the previous orbit determination program, although it has been modified to add a special case for the update of the quaternion at estimation epoch. This is due to the unit norm constraint that must be satisfied for the attitude quaternion at estimation epoch, which inhibits the use of a linear update. The solution adopted is a slight modification of the one given in [7]. 3 parameters $\mathbf{\Delta}=(\Delta_1, \Delta_2, \Delta_3)$ representing the update to the initial quaternion are estimated, instead of estimating the quaternion itself. Each parameter corresponds to a rotation around one inertial frame axis and its value is the half of the rotation angle around this axis. The updated quaternion is defined as:

$$Q_{new} = \cos(\|\Delta\|)Q + \frac{\sin(\|\Delta\|)}{\|\Delta\|}\mathbf{S}(Q)\Delta \quad , \quad \text{where} \quad \mathbf{S}(Q) = \begin{pmatrix} q_4 & q_3 & -q_2 \\ -q_3 & q_4 & q_1 \\ q_2 & -q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{pmatrix} \tag{2}$$

where the quaternion is expressed as the 4-dimension vector $Q=(q_1;\ q_2;\ q_3;\ q_4)$.

Once the quaternion update is applied, the value of the Δ-parameters is reset to zero and the *a priori* information equation is updated such that, for the next iteration, it attracts the value of the Δ-parameters to the direction from the current estimate of the quaternion at epoch to its original *a priori* value, weighted accordingly to the *a priori* variance.

The software has been developed such that any torque model can be easily added to the attitude propagator, although no torque model has been implemented yet. It is expected that the main contributor to comet torques is the comet outgassing.

2.3. Comet Orbit Propagation and Estimation

The new comet orbit propagator is an adaptation of the spacecraft orbit propagator (see section 2.4.) with a different set of force models affecting the body motion, which are: Newtonian direct and indirect central gravitational acceleration due to perturbing bodies [8], its relativistic corrections, and a new implementation of an asymmetric empirical model for acceleration due to comet outgassing defined in [9].

2.4. Spacecraft Orbit Propagation and Estimation

The spacecraft orbit propagator is reused from the previous software, which has been updated to support the comet as the orbit centre of integration. Before, only the Sun, the Solar System planets and the Moon could be set as the centre of integration of the spacecraft orbit. This has been generalized to support any celestial body as centre of integration, in particular the comet. The acceleration of the centre of integration is computed to derive the corresponding indirect acceleration on the spacecraft [10].

Additionally 2 acceleration models have been adapted from previous software: comet gravity field expansion and the drag due to the coma, the nebulous envelope of particles around the comet nucleus.

The coma drag is computed as the sum of the drag force generated by each of its species. The species information, density, position and velocity as a function of time, is provided by the engineering coma model implemented at ESOC [11].

The model of the comet gravitational field expansion is defined to have the first order coefficients (C_{10}, S_{10}, C_{11} and S_{11}) equal to zero because the comet-fixed reference frame is centred in the comet centre of mass. The second order coefficients are defined as a function of the inertia matrix parameters. If the comet-fixed frame were aligned with the principal axes of inertia then only C_{20} and C_{22} would be non zero. Nevertheless this has not been assumed because it might be difficult to *a priori* align the comet frame in which the landmarks are defined with the principal axes of inertia of the comet.

Therefore, the gravitational field expansion coefficients, the comet inertia matrix parameters and the comet attitude and orbit state affect the spacecraft propagation due to direct oblate acceleration (acceleration due to the gravitational field expansion of the comet) and the coma drag. The partial derivatives of these accelerations with respect to the 3 states (spacecraft orbit, comet attitude and orbit) are also computed and included in the variational equations.

The comet gravitational field expansion could, in principle, affect the comet orbit propagation due to indirect oblate accelerations. However, since the comet will not be close enough to any perturbing body, this effect is very small and, in practice, will be neglected.

The total set of acceleration models available for Rosetta orbit propagation is: Newtonian direct and indirect central gravitational acceleration due to perturbing bodies and its relativistic corrections, Newtonian direct and indirect oblate gravitational accelerations, solar radiation pressure, thermal radiation acceleration, coma drag and manoeuvres modelled as impulsive or continuous.

2.5. Observable Modelling

Rosetta navigation during the Comet Phase will be based on the following observable types, all supported in the new orbit determination program:

- Radiometric tracking from ground stations on Earth (mainly range and Doppler, occasionally ΔDOR) which have been used in all previous phases of the mission, and for all flying ESA deep space missions.
- Directions from spacecraft to the body centre reduced from optical images, which have been used in the asteroid fly-bys using a separated orbit determination program.
- Directions from spacecraft to landmarks on the comet's surface, for which a model has been developed for the Rosetta Comet Phase.

The relative measurements (pointing to comet centre and landmarks) are obtained from images taken by the on-board optical cameras. When the comet shape extends over few pixels in the image, the direction to the comet centre is well determined. As the spacecraft approaches the comet, its apparent size will increase, making more difficult to accurately determine the centre direction. Landmark observations are not affected by this effect. Therefore the centre direction observations will be used during the approach to the comet, while the landmark directions will be used for the rest of the mission around the comet.

The functions of image calibration, image correction, landmark identification and direction reduction (either to comet centre or to landmarks) [12] are transparent to the orbit determination software. Its input is directly the angular directions, either in inertial frame (right ascension and declination) or in camera frame (x/z and y/z, see below), from the spacecraft to the centre or the landmark respectively.

For the orbit determination process, it is necessary to model the expected observable as a function of the current value of the estimation parameters, and to compute also the partial derivatives of the expected observable with respect to the parameters that can be treated as uncertain. Next, the observation residual is computed and the observation equation is built and fed to the estimation filter. The model for the directions to the comet centre is described in [13], while the model for the landmark observable is briefly described below.

The values of the landmark observable are defined as *x/z* and *y/z*, where *(x; y; z)* are the coordinates in camera frame of the vector from spacecraft to landmark. *x* and *y* axes correspond to the horizontal and vertical directions in the camera's CCD, while *z* axis points in the direction of the camera field of view. The modelled direction from the spacecraft to the landmark in camera frame is computed as:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \mathbf{M_{cam}} \left(\mathbf{r_b} - \mathbf{r}_{sc} + \mathbf{M_b}^{-1} \boldsymbol{\kappa} - \left[(\mathbf{v_b} - \mathbf{v_{sc}}) \frac{1}{c} \left\| \mathbf{r_b} - \mathbf{r}_{sc} \right\| \right] \right) \tag{3}$$

where $\mathbf{M_{cam}}$ is the matrix of coordinate change from inertial to camera frame; $\mathbf{M_b}^{-1} = \mathbf{M_b}^{t}$ is the transpose of the matrix of coordinate change from inertial to body-fixed frame; $\mathbf{r_{sc}}$, $\mathbf{r_b}$, $\mathbf{v_{sc}}$ and $\mathbf{v_b}$ are the position and velocity vectors of spacecraft and body in inertial frame; $\boldsymbol{\kappa}$ is the landmark position vector in body-fixed frame; and c is the constant of speed of light in vacuum. The term in square brackets is an approximated correction for the planetary aberration effect caused by the combined movement of the body and the spacecraft when the image is taken. This correction is included for completeness, although it is not required for the Rosetta Comet Phase due to the small relative velocity. Finally, the modelled observable is:

$$\begin{pmatrix} obs_1 \\ obs_2 \end{pmatrix} = \begin{pmatrix} \cos b_3 & -\sin b_3 \\ \sin b_3 & \cos b_3 \end{pmatrix} \begin{pmatrix} x/z \\ y/z \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} \tag{4}$$

where b_1, b_2 and b_3 are parameters of corrections to the camera orientation that can be treated as uncertain. The camera frame orientation is derived from the spacecraft attitude determination and is provided as an input for the orbit determination. b_1 and b_2 represent a bias in the horizontal and vertical directions of the CCD, while b_3 represents a rotation of the image around the direction in which the camera is pointing.

The partial derivatives of the observable with respect to spacecraft orbit, comet orbit and attitude states at image time tag, landmark position and camera orientation biases are also computed. Applying the chain rule, the partials with respect to the states at observation time are multiplied by the partials of each state with respect to the dynamic parameters (obtained at the propagation steps), so that the full observation equation is built and can be fed to the estimation filter.

Initially the landmark positions in comet-fixed frame will be poorly known. As more measurements are obtained, the estimate of the coordinates will improve. This information will be stored in a landmark database containing the current estimates for the landmark positions and their covariance matrix. This database will be used as *a priori* input to the orbit determination process and, once a solution is obtained, it can be updated with the improved estimates.

3. Comet Phase Trajectory Design

This section presents an overview of the current status of the trajectory design and navigation analysis [14] that is being performed by the ESOC Flight Dynamics' Manoeuvre Optimization and Trajectory Design team. It covers up to the Lander Delivery Phase, selecting the baseline trajectories for each subphase in the Comet Phase (Tab. 3) and analyzing the navigation accuracy that is expected to be achieved. This analysis is currently ongoing since it has to be extended to the last phases of the mission.

The trajectories for each phase are chosen considering the phase objectives and satisfying some constraints. Eclipses and direct collision with the comet are avoided even in case of a manoeuvre interruption. Additionally, although it is not a mission constraint, occultation from Earth are also avoided such that constant communication link can be maintained. And finally, all trajectories must be suitable to be navigated using the NAVCAMs only, which are the baseline for Rosetta navigation. In real operations, it is planned to use also any image coming from the OSIRIS cameras (especially from NAC), which will improve the navigation results.

Table 3. Subphases of Rosetta Comet Phase

Phase Name	Reference start date	Distance to Comet [km]	Main objectives
Comet Approach	2014/05/21	From 1 million to 100	Detect the comet with on-board cameras, reduce relative velocity and bend trajectory towards the comet.
Comet Initial Characterization	2014/08/07	60 – 100	Identify first landmarks on the comet's surface, determine comet's shape and rotation state and obtain initial estimate of gravitational field.
Global Mapping	2014/08/23	20	Map at least 80% of the comet's surface and improve estimates of navigation parameters to allow for closer trajectories.
Close Observation	2014/09/15	5 – 10	Observation of candidate landing sites at closer distances to select the landing site.
Lander Delivery	2014/11/11	5 – 10	Deliver the lander to the selected landing site.
Relay	2014/11/11	To be defined	Maximize coverage of the lander to provide communications link to Earth.
Extended Monitoring	~2014/11/18	To be defined	Follow the comet in its excursion closer to the Sun, monitoring its increasing activity.

Each trajectory is analysed to evaluate the expected navigation performance, i.e. accuracy of orbit reconstruction and orbit prediction as well as estimation of other spacecraft and comet parameters. This is done by defining a "real world" model from which simulated measurements are generated to be fed to the estimator, which tries to fit the measurements with its "estimated world" model. Output of this process is the estimated value of the parameters (e.g. relative state, landmark coordinates, comet's attitude and gravitational field expansion, etc.) and a formal covariance matrix, providing an estimation of the error of the parameter estimation.

The navigation accuracy can be assessed in terms of the difference between the estimated parameters and the real world parameters, and comparing it to the obtained formal covariance. The biggest source of uncertainty in the orbit propagation and estimation is the mismodelling of the comet environment, such as comet's gravitational field and comet's outgassing (affecting both accelerations of comet and spacecraft). To reproduce this mismodelling effect in the analysis, a more complex model of comet's environment is used for the "real world", while a simplified model is used for the "estimated world".

3.1. Comet Approach Phase

The primary objective of this phase is to reduce the spacecraft-comet relative velocity from around 775 m/s to less than 1 m/s, while the distance is reduced from around 1 million km to 100 km. To perform this task, the total ΔV is divided in a series of rendezvous manoeuvres (RDVM#2) of decreasing size.

During the Comet Approach Phase it is expected to observe the comet with the on-board cameras which will provide information on the spacecraft-comet relative trajectory. Each observation reduces the relative position uncertainty in the plane perpendicular to the direction spacecraft-comet, but provides no information on this direction. Therefore the relative distance must be derived indirectly, from several observations taken from different sight angles. If the spacecraft trajectory pointed directly towards the comet, then no information on the relative distance would be obtained. To avoid this, the RDVM#1 target was to set the spacecraft in a fly-by trajectory 50,000 km away from the comet (at closest approach). The manoeuvres in this phase, apart from decreasing the spacecraft-comet relative velocity, will bend progressively the trajectory towards the comet, as more knowledge is obtained on the relative position.

Finally, the size of each manoeuvre is designed such that, if the next manoeuvre is missed (in case the manoeuvre is interrupted or cannot be performed for any reason), then the time to closest approach is sufficiently long to have margin to recover the spacecraft and command a new manoeuvre. Figure 3 represents the trajectory of Rosetta relative to the comet (in ecliptic projection) and the manoeuvres during May, June and July 2014 (there is a big difference in scale between each one). Table 4 lists the manoeuvre plan for this phase, including two additional manoeuvres for the transition to the next phase.

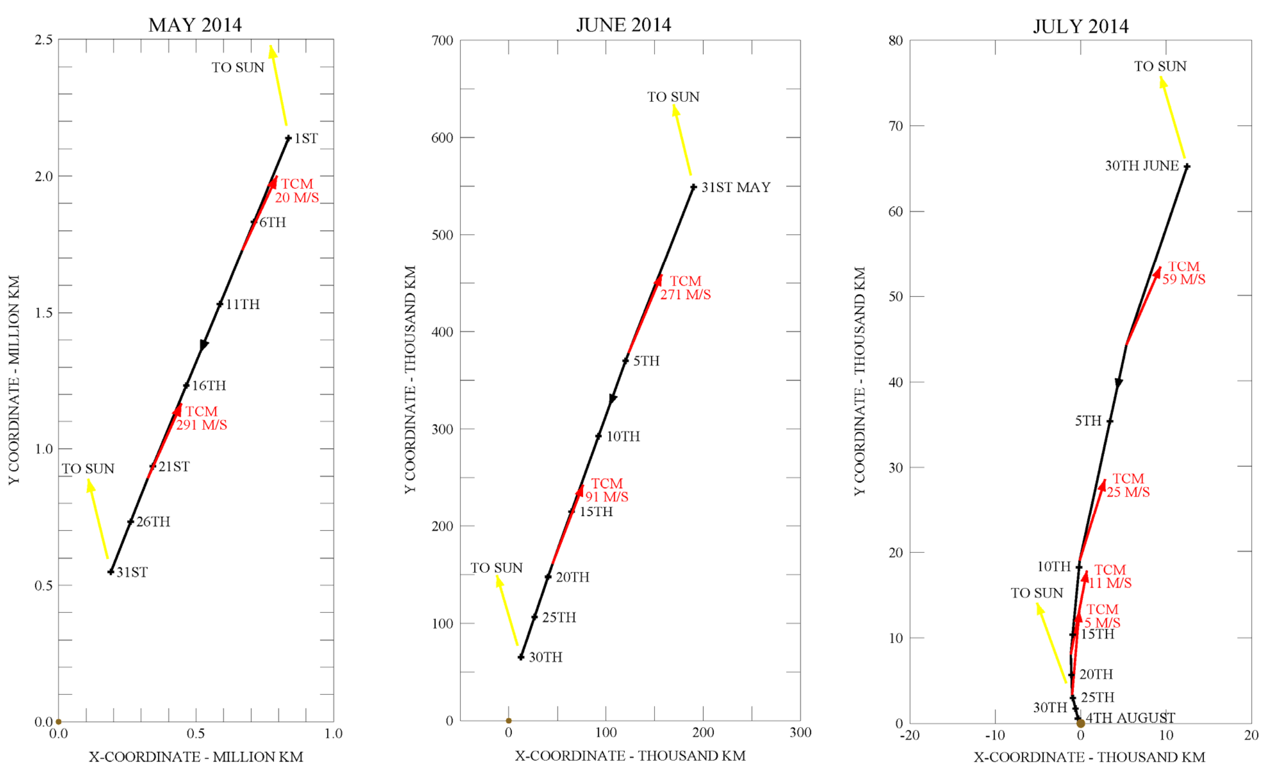

Figure 3. Trajectory of Rosetta relative to the comet and manoeuvres during approach

Table 4. Manoeuvre plan for Comet Approach Phase

Nr.	Manoeuvre	Date	Manoeuvre size [m/s]	Comet distance [km]	Sun distance [AU]	Earth distance [AU]
1	RDVM#2_test	2014/05/07	20	1,870,000	4.07	3.58
2	RDVM#2_1	2014/05/21	291	954,000	4.00	3.33
3	RDVM#2_2	2014/06/04	271	396,000	3.93	3.10
4	RDVM#2_3	2014/06/18	91	166,000	3.86	2.92
5	RDVM#2_4	2014/07/02	59	45,000	3.79	2.79
6	RDVM#2_5	2014/07/09	25	19,000	3.75	2.74
7	RDVM#2_6	2014/07/16	11	8,200	3.72	2.71
8	RDVM#2_7	2014/07/23	5	3,500	3.68	2.70
9	CIC-preinsertion	2014/08/05	2	400	3.61	2.70
10	CIC-insertion	2014/08/08	1	100	3.59	2.71

3.2. Comet Initial Characterization Phase

The main objective of this phase is to fly around the comet to identify landmarks on comet's surface, to determine comet's shape and rotation state and to obtain an initial estimate of gravity field. This navigation information is essential for safely flying trajectories closer to the comet in the next phase. It is desired that images of the comet nucleus are taken from different locations and with different illumination conditions. The optimum distance to take full images of the comet with the NAVCAMs is 60-70 km, since the highest resolution is achieved while assuring that the full comet nucleus fits inside the camera field of view. The selected trajectory for this phase consists of 4 hyperbolic arcs in a pyramid-like shape (Fig. 4) in the day side of the comet, having each arc a duration of 2 days with pericentre radius of about 60 km, except the first arc which starts at 100 km distance, for the transition from the previous phase.

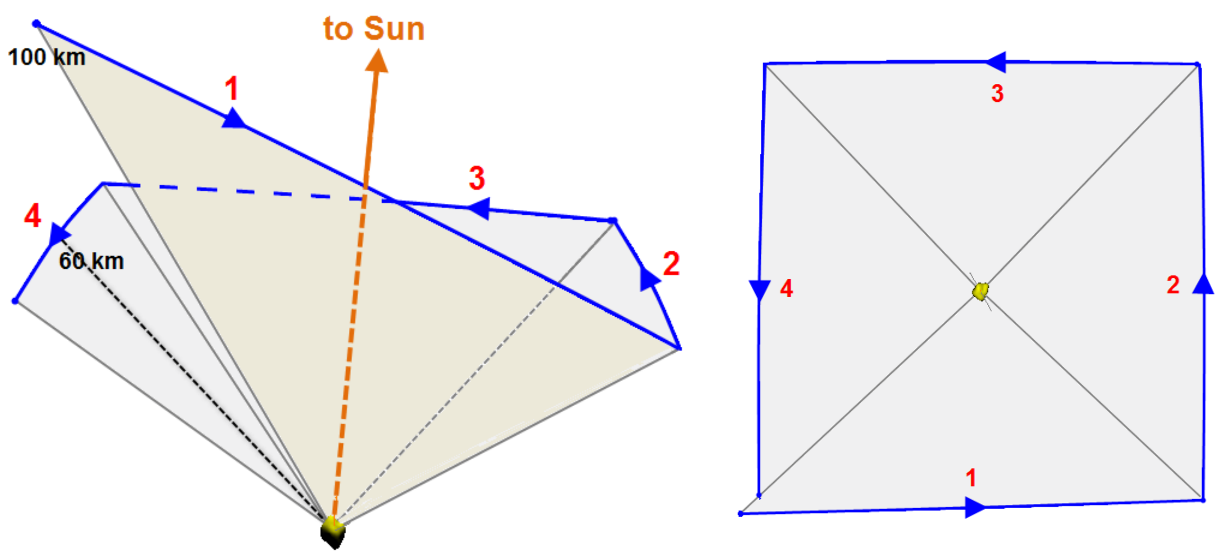

Figure 4. Initial characterization trajectory. Right image is the view from Sun direction

Each orbital plane is tilted 45 degrees from the Sun direction, so that the comet is observed with varying illumination conditions. At the end of each arc, a manoeuvre of about 0.7 m/s is required to switch to the next one.

The main advantages, for this phase, of hyperbolic arcs with respect to circular/elliptic arcs are a consequence of the higher spacecraft-comet relative velocity (around 0.5 m/s), making the trajectory more robust against insertion manoeuvre errors and mismodellings in the spacecraft dynamics around the comet. Additionally, with faster arcs, it is possible to observe the comet from different points of view in less time.

3.3. Global Mapping Phase

During this phase it is required to map at least 80% of the comet's surface with a resolution of 2000 pixels across the comet smallest diameter. Additionally, it is necessary to improve the knowledge on comet's dynamic and kinematics properties to allow for closer trajectories in the following phases.

For a nominal comet radius of 2km, it is necessary to observe the surface from a distance to the comet lower than 23km to achieve the required resolution with the NAVCAMs. The selected trajectory (Fig. 5) consists of four 180-degrees arcs of circular polar orbits of 20 km radius (7.5 days of period), in 2 planes tilted 30 degrees from Sun direction to avoid eclipses.

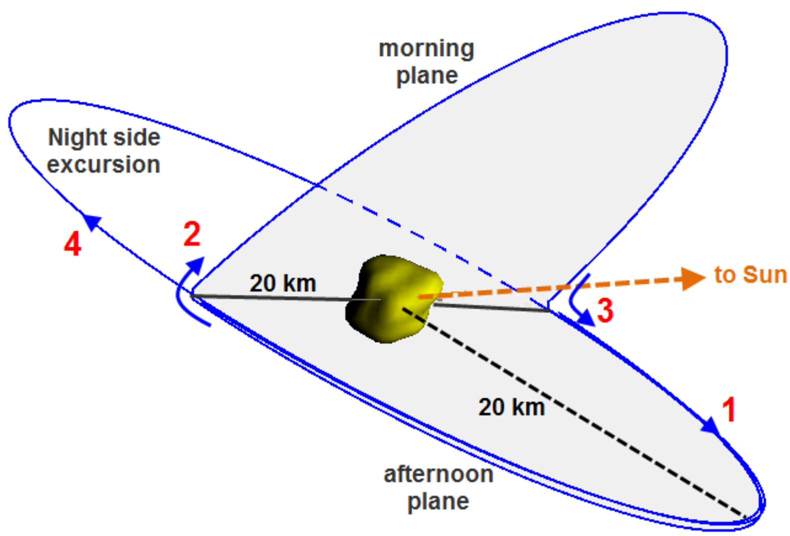

Figure 5. Global Mapping Phase trajectory including an excursion to the night side

Since it is preferred to keep the spacecraft in the day side of the comet, inversion manoeuvres will be performed when the spacecraft reaches the poles. Some excursion to the night side is possible just by skipping one manoeuvre. The inversion manoeuvres will switch also the orbit plane from the one in the morning to the one in the afternoon and vice versa. To avoid the possibility that a manoeuvre interruption could result in a relative velocity too small (risking collision to the comet), each manoeuvre is separated in two legs. With this more robust approach, the relative velocity is kept far from zero during the manoeuvre execution (Fig. 6) with an acceptable cost in ΔV.

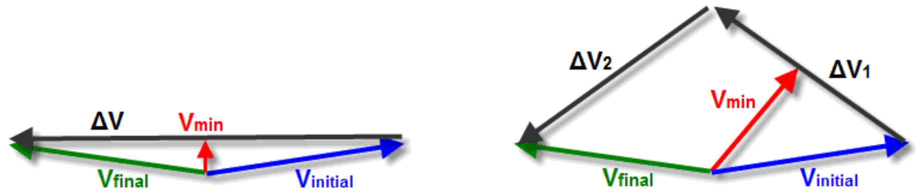

Figure 6. Comparison of minimum velocity (in red) during 1-leg and 2-leg manoeuvres

The orbital period of 7.5 days for this phase is derived from the comet reference gravity potential. In actual operations, when the comet gravity is precisely determined, the orbit radius will be adapted to keep the orbital period in 7.5 days.

3.4. Close Observation Phase

Based on the surface map obtained in the previous phase, candidate landing sites will be selected and prioritised by scientific interest. In this phase a very precise navigation is required to accurately point the instruments to the candidate landing sites. For this, it is intended to have long periods of flight without manoeuvres (to avoid degradation of navigation knowledge due to manoeuvre performance uncertainty) and to have continuous optical navigation data by avoiding excursions to the night side of the comet.

First, the candidate sites will be observed from a circular 10x10 km orbit with orbital plane close to daylight terminator plane (< 20 degrees) to avoid night side excursions. Once a candidate site is confirmed, a closer 10x5 km orbit will be flown to observe the potential landing region at pericentre. This orbit is the baseline for the lander delivery, so that this phase will also serve as a rehearsal, providing a measure of the navigation accuracy that can be achieved for the lander delivery.

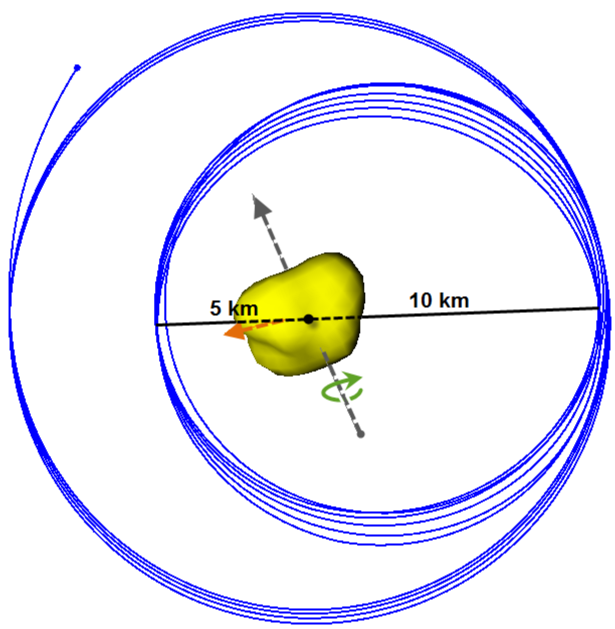

Figure 7. Close Observation Phase trajectory

3.5. Lander Delivery Phase

The lander delivery is still under analysis. There are restrictions from the spacecraft and the lander module on the delivery conditions that constrain the space of possible descent trajectories. The baseline approach is that the spacecraft will be left in a delivery orbit similar to the one from the Close Observation Phase, flying free of manoeuvres during several revolutions and when there is enough confidence in the navigation accuracy, the separation sequence will be triggered, possibly requiring last minute commanding for the timing and attitude profile for separation.

Another alternative under analysis is manoeuvring Rosetta right before separation, putting the spacecraft in a hyperbolic trajectory. This provides more flexibility in the possible landing trajectories, although it is operationally risky since the separation would be executed without assessing the performance of the manoeuvre, whose errors would degrade the descent trajectory accuracy.

Figure 8. Possible trajectories for lander delivery with (right) and without (left) manoeuvre

3.6. Relay phase

In this phase the spacecraft will provide relay services to the lander such that a communication link Philae-Rosetta-Earth can be used. Depending on the final delivery trajectory a relay orbit will be defined such that its operations workload is reduced in comparison to the previous phases.

3.7. Extended Monitoring Phase

In this phase Rosetta will monitor the nucleus, dust and gas jets from the onset to the peak activity near perihelion. Orbit design depends on safety considerations and scientific goals. The trajectories for this phase are still to be defined, although two different stages have already been identified.

First, right after the Relay Phase end, the activity of the comet is expected to be low. Rosetta will fly closed orbits at 10 - 20 km distance with the orbital plane close to the daylight terminator plane to reduce the effect of the drag in the spacecraft. Some excursions to the day side of the comet might be allowed for singular scientific objectives.

In the second phase, the comet is expected to be active, which will degrade the orbit prediction performance, and thus closed orbits are not considered safe. Rosetta will perform a series of fly-bys to the comet, following hyperbolic arcs with large relative velocity. The closest approach distance will be typically 70 km (far fly-bys). It is also being analysed to perform fly-bys at shorter distances, of about 10 km (close fly-bys), which would need a larger relative velocity to increase the spacecraft safety against uncertainties on the dynamics.

4. Conclusions and Outlook

An overview on the Rosetta Comet Phase has been presented. The navigation during this phase poses challenges that are new in ESA spacecraft operations. To the inherent difficulty of navigating close to a small body with not well known dynamics, has to be added the challenge of flying around the changing and increasing activity of the coma as the comet approaches the Sun.

The development of the new orbit determination software using optical navigation with landmarks is completed. The new software has been tested with a dataset of images from Rosetta fly-by of Lutetia, providing reasonable results. Currently it is under a validation process performed by an independent team at ESOC. Once it is validated as operational software, it is intended to be used for the orbit determination operations of the upcoming ESA deep-space missions.

Finally, the current status of the trajectory design and navigation analysis has been described in this paper. The manoeuvre plan and the trajectories for the first subphases are already consolidated, while the analysis is being continued for the last mission phases for the consolidation of the Lander Delivery conditions, and the design of the trajectories for the Relay Phase and the Extended Monitoring Phase.

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