TRAJECTORY PREPARATION FOR THE APPROACH OF SPACECRAFT ROSETTA TO COMET 67P/CHURYUMOV-GERASIMENKO

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Abstract: *When the Rosetta spacecraft approached comet Churyumov-Gerasimenko, almost nothing was known about its target's gravity field and rotation, except for the rotation period. Since knowledge of these parameters is essential for trajectory design, a flexible strategy had to be devised to cope with a large range of possible values. In addition, the strategy had to be robust against contingencies like missed orbit manoeuvres. The first simulations showed that the initial plan was not feasible. After several iterations, a strategy meeting these requirements was found. It consisted of a Comet Approach Phase, where the relative velocity was gradually reduced by orbit manoeuvres of decreasing size, and an Initial Characterisation Phase, where the physical parameters of the comet were determined from a sequence of hyperbolic arcs forming a pyramid-like orbit. These parameters would subsequently be used to adapt the trajectories for the next phase of the mission, where the spacecraft would be put into a bound orbit around the comet. The strategy chosen was successfully validated by a navigation analysis in which the operations that would be performed during the real approach were simulated, and finally confirmed when it was put into action during the real operations.*

Keywords: *Comet Approach, Rosetta, Churyumov-Gerasimenko, Optical Navigation*

1. Introduction

The plan to place a spacecraft in orbit around a comet and eventually deploy a lander on its surface presented ESA with a challenge nobody had ever faced: The trajectory of the comet was poorly known and most of its physical properties, in particular its mass, could be determined only once the spacecraft had reached its target. Furthermore, the time to do this was limited, since the lander had to be deployed before the comet became too active. This is in contrast to insertion into planetary orbit, where the trajectory and mass of the target body are well known in advance.

When the preparations for the approach of spacecraft Rosetta to the comet 67P/Churyumov-Gerasimenko started, only two physical parameters of the nucleus were known with good accuracy from observations using ground observatories and the Hubble Space Telescope [1]: the rotation period and the overall brightness. The latter gave an estimate of the size, which was, however, dependent on assumptions on the albedo and therefore much less accurate. Estimates for the mass were based on the size and the density, which could only be guessed, so the maximum and minimum estimates differed by a factor of more than 10. Estimates for the shape and the rotational state were based on light curve measurements [2], [3] and also afflicted with large inaccuracies.

Since an accurate knowledge of those parameters is essential for trajectory design, an approach strategy flexible enough to cope with a large range of possible comet characteristics had to be devised. This paper describes how, after several iterations, a strategy that met all requirements was achieved. It consisted of a Comet Approach Phase, where the relative velocity was gradually reduced by orbit manoeuvres of decreasing size, and an Initial Characterisation Phase, where the physical parameters of the comet were determined from a sequence of hyperbolic arcs forming a pyramid-like orbit. These parameters would subsequently be used to adapt the trajectories for the next phase of the mission, where the spacecraft would be put into a bound orbit around the comet.

The strategy chosen was successfully validated by a navigation analysis in which the operations that would be performed during the real approach were simulated in order to assess the accuracies to be expected for the optical navigation. The results confirmed the feasibility of the approach taken. The final confirmation of the strategy came during the real approach, when it was later put into action, without the need for any modifications. Detailed reports on the results and experiences during real operations are given in several other papers presented at ISSFD 2015 ([4], [5], [6], [7]).

2. Description of the Mission and the Spacecraft

Rosetta is the first spacecraft to orbit and deliver a lander on the surface of a comet. Its prime scientific objective is to study the origin of comets, the relationship between cometary and interstellar material, and the implications for the origin of the Solar System. To reach its target, the comet 67P/Churyumov-Gerasimenko, it had to follow a complex trajectory through the Solar System that included one Mars and three Earth swing-bys. Compared to the original mission to comet Wirtanen, which had to be abandoned due to an Ariane launch failure in 2002, there was one additional Earth swing-by, increasing the duration from the launch to the rendezvous with the comet from 9 to 10 years.

To fulfil its mission requirements, the Rosetta spacecraft is equipped with

- Two autonomous star trackers (STRs) for attitude determination,
- Three Inertial Measurement Packages (IMPs), each consisting of three ring-laser gyros and three accelerometers,
- Four Reaction Wheels (RWs),
- 24 bipropellant thrusters (10 N): 8 nominal + 8 redundant for attitude control and 4 nominal + 4 redundant for orbit control,
- A steerable high-gain antenna that allows communication with the ground in any attitude (except during orbit manoeuvres where some antenna positions are prohibited because of thruster plume impingement),
- Two large (1m×15m) Solar Array (SA) wings to allow operating the spacecraft up to Sun distances of 4.4 AU,
- Two Navigation Cameras (NAVCAM) for ground-based optical navigation,
- A suite of scientific instruments, one of which is OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System), which consists of two optical cameras: a Wide-Angle Camera (WAC), and a Narrow Angle Camera (NAC).

In the phase before comet rendezvous, due to the large Sun distance (up to 5.3 AU) the electrical power available on board was too small to operate the spacecraft. It was therefore put into a hibernation mode for 30 months, where only the on-board computer and some heaters were active to guarantee survival of the spacecraft.

Table 1: Rosetta cameras characteristics

	NAVCAM	**NAC**	**WAC**
Sensitivity	11 mag	>15 mag	> 15 mag
Field of view [deg]	5 x 5	2.2 x 2.2	11 x 11
Pixels	1024 x 1024	2048 x 2048	2048 x 2048
Resolution (bit/pixel)	12	16	16

The properties of the Rosetta cameras are summarised in Table 1. Although all of these cameras were planned to be used for optical navigation, the scientific cameras (NAC and WAC) are not redundant, so their availability could not be guaranteed. Therefore all simulations were done using only the NAVCAM. This assumption was pessimistic, since in real operations, the use of the scientific cameras with their better performances would improve the accuracy of the navigation results.

3. Analysis Approach and General Assumptions

3.1 Navigation Analysis

To assess the accuracy obtainable for the spacecraft and comet orbits and the cometary parameters, an extensive number of simulations were performed for all phases of near-comet operations. There were two types of simulations, closed-loop and open-loop.

3.2.1 Closed-Loop Simulations

In a closed-loop simulation the operations to be performed during comet approach are simulated as closely as possible. For each orbit manoeuvre, there is a cut-off time specified in the planning process, typically about 2 days before the time of the manoeuvre, that denotes the time of the last observation that goes into the preparation of the manoeuvre and the following part of the trajectory. The observations are then used on ground to estimate the state of the spacecraft and the comet at the cut-off time, and the result is used to prepare the commands for the orbit manoeuvre and the attitude control for the next part of the orbit. The commands must then be uplinked to the spacecraft before they can be executed. The time at which the new commands replace the commands of the previous planning cycle, the so-called start time, is e.g. about 1 day before the time of the manoeuvre; and the attitude profile must cover the time interval from the start time to the end time, which is equal to the start time of the next planning cycle, when the new attitude profile becomes valid. This means that there is a time period (from cut-off to start time) when the ground knowledge of the orbit is already improved by the latest observation, but the attitude profile on board is still based on the orbit propagated from the previous estimation, and therefore less accurate.

The navigation analysis follows the same approach. To generate the simulated observational data, a simulated “real world orbit file” is maintained after each estimation step by propagating the state from the previous "real world orbit file" over the manoeuvres generated from the result of the estimation. To account for the performance errors of the manoeuvres in size and direction, a random error (typically 1% in magnitude and 1° in direction, all 1σ) is applied to the delta-V obtained from the optimisations. For manoeuvres under 50 cm/s, a random magnitude error of 0.5 cm/s (1σ) simulates the readout noise of the accelerometers.

For the comet, the model for the shape, rotation axis and rotation period (pure rotation), as given by Lamy et al. [1] was used, which models the comet as a polyhedron. To model the gravitational field of the comet, a constant mass density of 370 kg/m^3 was assumed. The gravitational constant of the model comet is 806.8 m^3/s^2, the effective radius is 1.907 km and the rotation period is 12.72 hours.

The estimation software uses either measured directions from the spacecraft to the comet centre or to landmarks on the surface of the comet (depending on the distance) and radiometric (geometric distance to simulate ranging, and Doppler) measurements to calculate the state vector at a specified instance of time during the measurement period (epoch) and other parameters of the comet by a least-squares fit. The results of this estimation are the most probable a-posteriori values for the estimated parameters, together with a formal covariance matrix. One such estimation step is performed after each of the orbit manoeuvres. The initial values and a-priori covariances for the estimation are obtained by propagating the results of the previous step to the epoch of the new step.

For the purpose of the navigation analysis described in this paper, the direction vectors to the comet centre or landmarks were treated as given measurement input. The process used to derive those measurements from camera input was outside the scope of the analysis and is described in [4] and [5].

In general, with increasing number of measurements the accuracy of the "estimated world" is improved and the formal covariance is reduced. Provided that the modelling of the estimator matches the "real world" the formal covariance matrix is a reliable indicator of the typical error in the estimated parameters. This is not the case when there are mismatches between the "real world" model and the "estimated model". In such case, the true errors in the estimated parameters may largely exceed the standard errors provided by the covariance and the covariance matrix does not provide a reliable indicator of the errors in the estimate.

Errors in the modelling are inherent to the navigation around the comet. In particular, the "estimation model" for the comet gas drag forces during operations will certainly not match the real world, due to the unpredictability and irregularity of the coma. These modelling errors are not reflected in the formal covariances, which therefore become meaningless as soon as the effect of the coma becomes significant. This situation is representative of what can be expected during normal operations.

3.2.2 Open-Loop Simulations

To reduce the effort implied by closed-loop simulations, another type of simulation was devised: the open-loop simulation. Here the real orbit is generated for the whole phase at the beginning of the simulation. At each step of the simulation, measurements are generated from the real orbit and a least-squares estimation of the state is performed, like in closed-loop simulations, and the estimated state is propagated to the time of the next simulation. Since the error in the manoeuvre performance cannot be applied to the real orbit (which is fixed), it is instead applied to the estimated orbit. Although not realistic, this procedure has the same statistical effect on the difference between the real and the estimated orbit, so it can be used to assess the accuracy of the estimation.

To validate this approach, the initial simulations were performed both in open and closed loop, and the results were compared to each other. The comparison confirmed that the open-loop method is valid, so further simulations were run in open loop only. By this approach, the effort needed was significantly reduced.

4. The Comet Approach Phase

The Comet Approach Phase started after Rosetta's wake-up from hibernation and the subsequent check-out and de-hibernation of all spacecraft systems. The objective of this phase was to decrease the relative velocity between the spacecraft and the comet from about 775 m/s to nearly zero with a sequence of orbit manoeuvres, while the spacecraft was approaching the comet from a distance of about 1,000,000 km to about 100 km. The first manoeuvre of this sequence was scheduled at the time when the comet reaches a sun distance of 4.0 AU as a compromise between fuel consumption and the aim to have the rendezvous with the comet as early as possible.

4.1 Trajectory Design Drivers and Strategy

4.1.1 Comet Detection

Since the position of the comet was initially known only to an accuracy of about 15,000 km (1σ), optical navigation using camera images was essential to reach the target. Both the NAVCAM and the OSIRIS WAC were used for this purpose, but since OSIRIS is not redundant on the spacecraft, the navigation analysis was done under the assumption that only the NAVCAM could be used. The first detection of the comet should be as early as possible, preferably before the first manoeuvre, in order to adapt to future manoeuvres to the latest estimation of the comet position.

When the Rosetta mission was designed, the performance of the NAVCAM was not yet known, so mission analysis was performed under the assumption that the maximum distance for comet detection was only 100,000 km. This led to a split of the Comet Approach Phase into a Near Comet Drift (NCD) Phase, where all manoeuvres were to be performed without comet images, based only on the predicted orbit of the comet, and a Far Approach Trajectory (FAT) Phase, during which the navigation was to be based on optical images. The actual performance of the NAVCAM, as specified by the manufacturer and verified during the two asteroid fly-bys (and also later during real operations, see [4]), meant that comet detection was already possible at a distance of about 1,225,000 km, i.e. shortly before the first manoeuvre, and with the NAC the comet could be detected after de-hibernation, so the distinction between NCD and FAT became meaningless. Nevertheless, these labels were retained in the designation of the various manoeuvres, for consistency with previous analyses.

4.1.2 Impact Vector

During approach, the navigation camera takes some measurements on the position of the comet. Each single measurement reduces the uncertainty in the plane perpendicular to the direction spacecraft-comet, but leaves this particular direction unresolved. In order to reduce the uncertainty in this direction, several images with different sight angles are needed.

The driver of the variation of the sight angles is the impact vector. When the impact vector is large, the sight angle from two different points of the trajectory is higher, and the uncertainty of the comet is smaller. If the impact vector is 0, the sight angle is 0 and the knowledge in the distance satellite-comet is not improved by optical measurements. Figure 1 shows the uncertainty (yellow area) of the position of the comet after two measurements, for two different impact vectors. They show that the bigger the impact vector is, the smaller the uncertainty is.

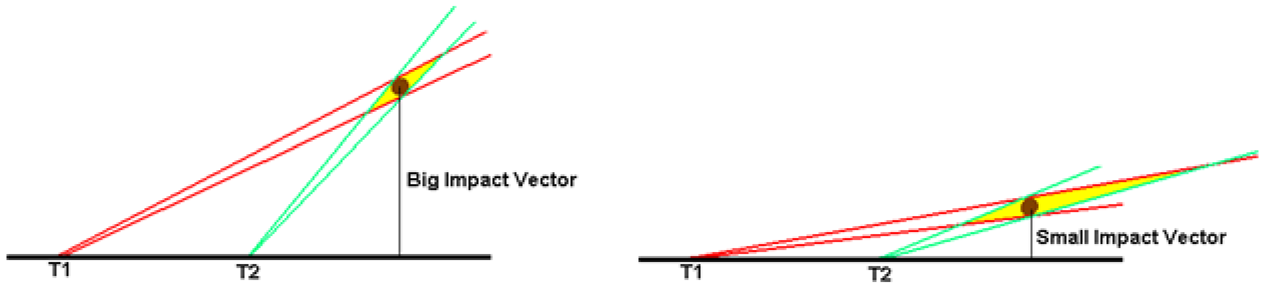

Figure 1: Effect of impact vector on navigation accuracy

For the definition of the nominal impact vector, the uncertainty in the relative comet-S/C position shall be considered, such that also in a worst case scenario the resulting impact vector is large enough for navigation (see Figure 2).

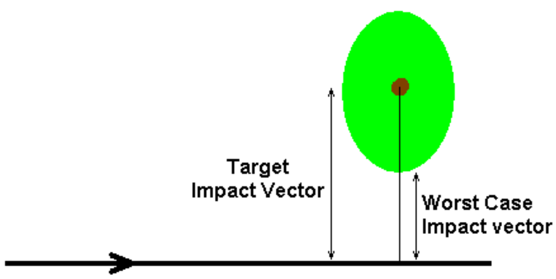

Figure 2: Impact vector depending on position uncertainty

For the later approach manoeuvres, in addition to the needs for navigation, the impact vector shall also be such that the S/C trajectory is guaranteed to be collision free (also in case a manoeuvre is interrupted or aborted).

The impact vector is reduced during the approach manoeuvres, such that the trajectory is bended progressively towards the comet nucleus.

4.1.3 Time to Closest Approach

A conceivable contingency during the approach phase is the inability to perform manoeuvres for certain duration. This can be caused e.g. by a problem on the propulsion system. If the contingency cannot be resolved before the spacecraft passes by the comet, additional fuel must be spent to revert the direction of the velocity of the spacecraft relative to the comet. This additional fuel consumption increases with the manoeuvre size and would be prohibitively large for the first, largest manoeuvres. In addition, navigation is from the dark side of the comet, such that no optical measurements can be obtained for the drift back period. The recovery could take serveral weeks with a corresponding delay of the comet landing. This would significantly increase the risk of failure due to higher activity of the comet.

A measure of the robustness of the trajectory strategy to such contingency is the time to closest approach (in the absence of manoeuvres). The time to closest approach represents the absolute maximum duration of manoeuvre inability that can be afforded. The time to closest approach obviously decreases monotonously with time (outside manoeuvres) but increases when the relative velocity is reduced (at manoeuvres).

4.1.4 Trajectory Strategy

The original manoeuvre schedule devised before launch is shown in Table 2. The first and largest of the manoeuvres has a time to closest approach of only 5 days.

Table 2: Original manoeuvre schedule for Comet Approach Phase

Nr.	Manoeuvre	Date	Man size [m/s]	Time to closest approach (days)	Comet distance [km]
1	NCD#1	2014/05/18	366.1	5.0	338,000
2	NCD#2	2014/05/21	213.8	6.5	231,000
3	NCD#3	2014/05/24	103.4	10.3	180,000
4	NCD#4	2014/05/27	47.7	18.3	154,000
5	FAT#1	2014/06/17	13.4	14.7	64,000
6	FAT#2	2014/06/27	11.6	9.6	31,000
7	FAT#3	2014/07/07	11.4	3.8	8,600
8	FAT#4	2014/07/12	13.1	1.9	2,500

This was considered too risky, so after several iterations a new schedule was chosen (see Table 3), consisting of 9 manoeuvres plus a test manoeuvre.

Table 3: Updated manoeuvre schedule for Comet Approach Phase

Nr.	Manoeuvre	Time	Man size [m/s]	Time to closest approach (days)	Comet distance [km]
0	NCD-test	2014/05/07	20.0		1872000
1	NCD#1	2014/05/21	290.9	14	963000
2	NCD#2	2014/06/04	271.0	10	401000
3	NCD#3	2014/06/18	90.8	10	167000
4	FAT#1	2014/07/02	58.8	5	45000
5	FAT#2	2014/07/09	24.9	5	19000

6	FAT#3	2014/07/16	10.7	5	8200
7	FAT#4	2014/07/23	4.6	5	3500
8	CAT-preinsertion	2014/08/03	2.8	3	350
9	CAT-insertion	2014/08/06	1.0		120

The names of the manoeuvres have been retained, although formal distinction between the NCD and FAT phases no longer applies. The time to closest approach decreases as the manoeuvres become smaller, thereby reducing the delta-v impact of a delay. Since the date of the first manoeuvre was essentially fixed (see above), the comet distance at that date had to be increased (by re-targeting the last pre-hibernation manoeuvre), and the duration of the Comet Approach Phase (from first to last manoeuvre) had to be increased from 55 to 77 days. A part of that increase is because the Comet Approach Phase now ends closer to the comet due to the modified strategy for the Initial Characterization Phase (see below).

4.2 Navigation Analysis

4.2.1 Assumptions

As explained above it was expected that comet detection with the CAM would be possible 3-4 days before the first manoeuvre of the approach. Until beginning July 2014, the comet would appear as a point like object (angular diameter smaller than one pixel). After that, the apparent diameter of the nucleus would grow quickly, so that towards the end of the approach phase features might be already identified in the images. For the purpose of the navigation analysis it was conservatively assumed that for the whole approach phase only comet centre information would be derived from CAM images.

The assumed frequency of camera images is 1 image per day until the FAT#1 manoeuvre, and one image every 6 hours afterwards. The assumed 1σ error for the comet centre direction was 1 pixel or 1/10 of the apparent diameter of the nucleus, whatever was larger. The latter was done to account for the uncertainties in determining the centre-of-mass direction from resolved images of the nucleus.

4.2.2 Results

As explained in section 2.1, two types of estimates are performed: a-priori and a-posteriori. For the a-priori estimate, data is collected up to the cut-off time prior to a manoeuvre for estimating the current state. A propagation is performed up to the cut-off time of the next manoeuvre and the predicted and “real world” state vectors are compared.

Two components are reported for position and velocity errors:
- Longitudinal: this is the component in the direction towards the comet
- Transversal: this is the component orthogonal to the direction towards the comet

Table 4 provides a summary of the navigation results (a-posteriori). Each row of the estimation corresponds to a manoeuvre in the approach phase. Since the drag force by the coma is negligible during the Comet Approach Phase and all other forces can be accurately modelled, the formal covariances of the estimation results are representative of the accuracy achievable;

therefore only the formal 1σ errors are reported. The actual errors depend on the random measurement errors chosen by the simulator, so their concrete values for a given simulation run are not important. In all cases, they were compatible with the sigmas.

Table 4: Approach phase a-posteriori navigation errors

	Position error (1σ) [km]		**Velocity error (1σ) [mm/s]**	
Man Nr.	**Longitudinal**	**Transversal**	**Longitudinal**	**Transversal**
1	6900	117	710	290
2	6300	52	690	165
3	3700	21	470	103
4	390	7.3	280	62
5	96	3.6	72	29
6	65	1.17	18.3	15.6
7	29	0.49	7.1	8.1
8	13.3	0.97	3.1	2.8
9	12.4	0.197	2.86	1.85

5. Initial Characterisation Phase

In the original plan it was foreseen to insert Rosetta directly into a circular orbit around the comet at the end of the approach and perform a detailed characterisation of the comet from that orbit. A near-polar orbit was chosen so that all illuminated regions of the comet can be observed under good viewing conditions. This plan required obtaining an estimate of the mass and the rotation axis direction during the short phase before orbit insertion, termed the Close Approach Trajectory (CAT) phase, when Rosetta is close enough to the nucleus so that landmarks can be discerned in the camera images and the orbit of the spacecraft is noticeably influenced by the gravity field of the comet. The navigation analysis performed for this approach showed that the attitude of the comet could not be accurately estimated early enough to identify the target plane. For this reason, the CAT phase was replaced by an Initial Characterisation Phase to characterise the comet before the selection of the target plane and orbit insertion.

5.1 General Description of the Phase

The main objectives of the Initial Characterisation Phase were:

- To identify landmarks on the comet surface and estimate their position.
- To determine the rotation state of the comet.
- To determine the shape of the comet.
- To obtain a first estimate of the gravity potential, allowing for future navigation of closer orbits around the nucleus.

To achieve the above objectives, it was required to obtain full images of the nucleus with the best possible resolution with a wide variety of observation conditions (i.e. comet observed from different locations with different illumination conditions). For operations with NAVCAM, the spacecraft has to be placed at a distance of about 90-120 km from the nucleus in order to contain the comet largest diameter. From those distances, accounting for navigation errors, at least 50% of the NAVCAM images were expected to contain the full nucleus. It was considered that these images would be enough to identify a first set of landmarks in the comet surface and to reconstruct the comet shape (see [5]).

After an initial period of about 10 days, the distance to the nucleus was reduced to 50-70 km to allow for observations with better resolution. At these distances, the nucleus did not fit in a single image. From this phase onwards, NAVCAM images did not need to contain the complete comet nucleus, as long as they contained enough information for navigation (i.e. landmarks could be identified).

5.2 Trajectory

5.2.1 Trajectory Drivers and Constraints

The first idea to perform the initial characterisation from a circular orbit was found not adequate for the following reasons:

- The estimates of the comet gravity potential obtained before insertion were too poor to plan accurately circular orbits.
- In addition, the approach velocity of ~1 m/s is large compared to the orbital velocity (a few cm/s). Manoeuvre errors at the insertion would result in a trajectory shape significantly different from circular.
- The orbital velocity is small for circular orbits. The illumination conditions change only slowly. To acquire images with a wide variety of observation conditions from a circular orbit, a long phase duration would be required.

Because of the above reasons it was decided to use hyperbolic trajectories with a relative velocity of ~0.5 m/s. Such trajectories offer the following advantages:

- Lower sensitivity to errors in the gravity potential.
- Lower sensitivity to insertion manoeuvre errors.
- Rapid excursions around the comet nucleus.
- The hyperbolic trajectory arcs can be selected such that the spacecraft remains on the day side of the nucleus, to give good viewing conditions.

A characteristics of hyperbolic trajectories is that they fly away from the nucleus. For this reason, periodic manoeuvres are performed, changing the trajectory from one hyperbolic arc to the next, such that the S/C remains close to the nucleus. On the other hand, hyperbolic trajectories ensure escape from the comet with relatively good illumination conditions in case of problems in the S/C.

5.2.2 Trajectory Strategy

The selected strategy for comet initial characterisation is as follows:

- The comet initial characterisation is performed from a sequence of 8 hyperbolic arcs. The first 3 arcs fly a closed triangle at 90-120 km. The last 3 arcs fly a closed triangle at 50-70 km. The two intermediate arcs fly arcs with intermediate conditions.
- The relative velocity of the S/C is ~0.5 m/s.
- The pericentre of each arc is at about 90 km radius for the first three arcs and 50km for the last three arcs.
- The S/C flies 3 or 4 days on each arc.
- Insertion in the first arc is planned nominally at a distance to the nucleus of 120 km.
- A manoeuvre of about 0.8 m/s is required to switch from one arc to the next.
- The orbital plane of each arc is tilted ~30 degree from the Sun direction.
- The comet-spacecraft vector describes a pyramid shape on the Sun side of the comet (see Figure 3).

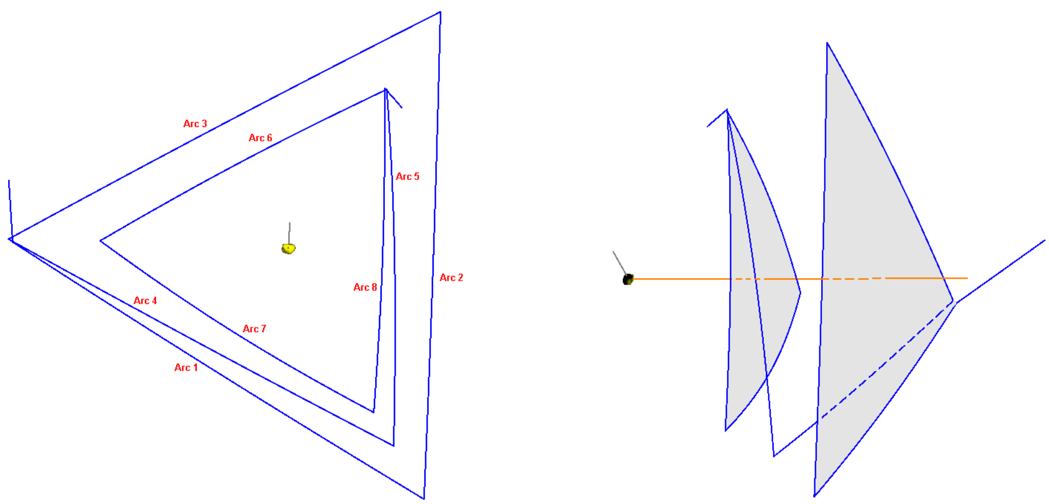

Figure 3: Comet initial characterisation geometry

A summary of the manoeuvres for the characterisation phase is provided in Table 5.

Table 5: Manoeuvres during the initial characterisation phase

Manoeuvre	Time	Man size [m/s]
CAT-insertion	2014-08-06	1.0
CAT-pyramid#1	2014-08-10	0.87
CAT-pyramid#2	2014-08-13	0.87
CAT-pyramid#3	2014-08-17	0.83
CAT-pyramid#4	2014-08-20	0.72
CAT-pyramid#5	2014-08-24	0.60
CAT-pyramid#6	2014-08-27	0.58
CAT-pyramid#7	2014-08-31	0.58

The observation conditions for the pyramid strategy are optimal. The comet is observed from moderate phase angle, at adequate distances, and from a wide range of latitudes.

5.3 Navigation

5.3.1 Assumptions

During the initial characterisation, images of the full comet nucleus were taken once per hour. This frequency was driven by the needs for the purpose of landmark identification and comet shape reconstruction. For navigation analysis fewer images are needed; only one image every 4 hours has been considered.

For the navigation analysis here it has been assumed that for each arc, data are collected until the cut-off time before the manoeuvre defining the beginning of the arc, which is also used as the epoch for the estimation, and the state is propagated over the manoeuvre up to the start time of the next commanding cycle.

5.3.2 Results

The navigation results for the orbit are reported in Table 6. Due to the mismodelling of the drag forces, the formal covariances are no longer representative of the expected errors. Therefore 10 independent simulations were run, and the root-mean-square (RMS) values were calculated for the longitudinal position errors and offpointings. Each error value is reported at the data cut-off time, the start time and the end time of the arc. The values at cut-off time correspond to the estimation results and are representative for the accuracy of the reconstruction of the orbit. The start and end time values are derived by propagating the estimated orbit from the cut-off time into the future and determine how accurately the orbit can be predicted. In particular, the offpointings at start and end time show how the pointing accuracy changes during the arc.

Table 6: Navigation errors of orbital parameters during initial characterisation

	RMS longitudinal error [km]			**RMS offpointing [°]**		
Pyramid arc	**Cut-off**	**Start**	**End**	**Cut-off**	**Start**	**End**
#1	0.847	0.742	1.701	0.022	0.164	1.929
#2	0.198	0.384	1.606	0.046	0.213	1.672
#3	0.524	0.638	1.908	0.066	0.096	1.447

The large prediction errors at the end of the pyramid arcs are mainly driven by the uncertainties in the execution of manoeuvres. In particular, the offpointings of up to 2° mean that at the end of each arc, only a part of the comet may be contained in the image. This was considered acceptable, since the visible part suffices for the purpose of optical navigation, and for comet shape reconstruction there are still enough complete images left during the earlier parts of the arcs. Also, the error estimates are based on pessimistic assumptions on the manoeuvre performances. During real operations, it turned out that most of the images contained the full nucleus, while for a few a small part of the comet was clipped.

Table 7 shows the navigation results for several parameters of the comet: the inertial direction of the rotation axis, the phase of the rotation, the rotation rate, the mass, and the landmark positions. Again, the errors shown are RMS values over 10 simulation runs. In case of landmark positions, the RMS was taken over all landmarks that could be observed with sufficient accuracy (formal 1σ error less than 100m).

Table 7: Navigation errors of cometary parameters during initial characterisation

	RMS errors of				
Pyramid arc	**Axis direction [°]**	**Phase [°]**	**Rate [°/day]**	**Gravitational constant [m^3/s^2]**	**Landmark pos. [m]**
#1	0.206	0.183	0.33501	135.4	31.33
#2	0.064	0.134	0.02304	89.3	22.57
#3	0.031	0.094	0.00963	90.1	9.36

Due to time constraints, no navigation analysis has been performed on the arcs #4 to #8. Since the prediction errors are mostly driven by the performance of the manoeuvre and the manoeuvres slightly decrease in size, it was expected to get a slightly better position prediction than in the arcs #1 to #3. On the other hand, since the distance to the comet is smaller, the pointing error would be degraded. To accommodate for this, a different imaging strategy was implemented: four images, forming a 2×2 raster, were taken every four hours to ensure that the full nucleus was visible at every observation.

6. Conclusions

In preparation for the approach of spacecraft Rosetta to comet 67P/Churyumov-Gerasimenko, an extensive number of simulations were performed. These included both closed-loop and open-loop simulations, where the more realistic closed-loop simulations were used to validate the idea of open-loop simulations, which are less realistic but require less effort.

The first simulations clearly indicated that the original plan, which foresaw a direct insertion into a bound orbit at the end of the approach phase, was not feasible since the comet mass and attitude could not be determined with sufficient accuracy before the insertion manoeuvre. Instead, after several iterations, a new strategy was devised: The initial characterisation of the comet was done from hyperbolic arcs at cometocentric distances between 50 and 120 kilometres. The velocity in these arcs was chosen such that the influence of the initially poorly known comet gravity force on the spacecraft orbit was large enough to provide an accurate determination of the comet mass, but still small enough to allow a reasonably accurate orbit prediction. Orbit manoeuvres were performed regularly to keep the spacecraft close to the comet, in such a way that the comet-spacecraft vector formed two pyramids with the nucleus at the apex.

From these pyramid orbits, the mass, rotational state and shape of the comet could be estimated. Moreover, landmarks on the surface of the nucleus could be identified with sufficient accuracy for a safe insertion into a bound orbit. Following the insertion, the spacecraft entered the Global Mapping and the Close Observation phases, in which the knowledge about the comet properties was further improved by observations from successively closer orbits around the comet.

The validity of the revised strategy was finally fully confirmed when it was put into action during the actual operations, without the need for any modifications. All orbit manoeuvres during approach performed well within the expected uncertainties ([6], [7]), the comet was detected at the earliest possible stage using the OSIRIS NAC and the derivation of optical measurements from camera images worked flawlessly ([4], [5]).

7. References

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