SpaceOps 2010 Conference
 <i>Delivering on the Dream</i>
 <i>Hosted by NASA Mars
25 - 30 April 2010, Huntsville, Alabama

AIAA 2010-2167

Science Operations Planning of the Rosetta encounter with Comet 67P/Churyumov-Gerasimenko

Michael Küppers, Kristin Wirth, David Frew, and Gerhard Schwehm
European Space Astronomy Centre (ESAC), ESA, 28691Villanueva de la Cañada, Madrid, Spain

Claire Vallat, Viney Dhiri, Jorge Diaz del Rio Garcia, and Mike Ashman
Vega Group, contracted to ESA, European Space Astronomy Centre (ESAC),28691Villanueva de la Cañada, Madrid, Spain

Juan Jose Garcia Beteta
GMV, contracted to ESA, European Space Astronomy Centre (ESAC),28691Villanueva de la Cañada, Madrid, Spain

and

Rita Schulz
European Space Technology Center, ESA, 2200 AG Noordwijk,,The Netherlands

Rosetta is a cornerstone mission of the European Space Agency (ESA). It was launched in March 2004 and will rendezvous with comet 67P/Churyumov-Gerasimenko (C-G) in 2014. Rosetta consists of an orbiter and a lander. Rosetta will meet Comet C-G early 2014 at a heliocentric distance of approximately 4 AU after wake up from a 2.5 year phase of deep space hibernation. The lander will be delivered to the surface in Nov. 2014 at around 3 AU from the sun, while the orbiter will continue to follow the comet on its orbit through perihelion until it reaches 2 AU outbound by end of 2015. The Science Operations and Data Handling Concept (SODH concept) deals with the 14 months between lander delivery and end of the nominal mission, the so called escort phase. That mission phase is extraordinarily complex: Approaching the sun the comet becomes increasingly active and its environment is expected to change dramatically and unpredictably. Therefore continuous monitoring of the comet (based on the science data returned) is required to mitigate risks on the spacecraft, mainly due to dust particles emitted from the nucleus. On the other hand, the evolving comet activity poses great scientific opportunities and payload operations are expected to react and adapt in response to these changing activities. In addition, the activity of the comet together with its small size (about 2 km radius) implies that the trajectory of the spacecraft relative to the nucleus may not be predictable for extended periods of time and that active orbit control will be required. The SODH concept foresees a closed loop system between operations planning and data analysis. Scientific operations planning is centralized at the Rosetta Science Operations Centre (RSOC), with an information repository at its core, containing operational inputs provided by the Principal Investigator (PI) teams that are responsible for the payload instruments. At the comet we expect to execute mostly predefined operation blocks. Changes in the comet environment and results of scientific observations feed back into the planning process. The planning process has already started with the baseline planning. It is based on the Rosetta Science Themes, representing the Science Objectives for Rosetta and the associated measurements by the various payload instruments. The instrument teams provide geometrical constraints (e.g. illumination requirements) and resource estimates (power, data volume, number of telecommands) needed for each measurement. The escort phase is divided into several phases. The proposed measurements are ordered based on their contribution to the science objectives to be covered during a given phase. The result will be the baseline plan of typical trajectories and pointing modes for each mission phase and an estimate of required resources, e.g. integration time and data volume. Expected conflicts and prioritization needs will also be identified in this stage. The

baseline plan and the information repository are used to define the long term plan, a complete operations schedule for the escort phase. The actual operations planning will then be performed as a continuous adaptation and modification of the long term plan using predefined operational blocks. First the long term plan trajectory will potentially be modified according to latest information on the cometary environment and scientific results. At this point a conflict-free operations plan exists that can be executed on the spacecraft. If time permits, further iterations will be performed to further optimize the plan, fixing first the attitude profile and then the payload operations.

I. Introduction

The International Rosetta Mission to Comet 67 P/Churyumov-Gerasimenko (C-G) was launched on 2 March 2004. The spacecraft consists of an orbiter with 12 scientific instruments and a Lander (called PHILAE) with its own suite of 10 instruments[1].

The spacecraft performed several swing-by maneuvers where the gravity of the planets Earth (3×) and Mars (1×) were used to change the course of the spacecraft. While science measurements were performed during the swing-bys, the priority there lied on spacecraft activities. Two asteroid flybys are secondary science targets of the mission: On 5 September 2008 Rosetta passed by asteroid 2867 Steins[2-3], and on 10 July 2010 it will flyby asteroid 21 Lutetia. From mid-2011 to January 2014 the spacecraft will be in deep space hibernation.

Rosetta is scheduled to arrive at the target comet in spring 2014. After a period of a few months to characterize the comet environment and its surface, it will deliver the PHILAE Lander. The aim is to deliver the Lander at a distance comet – sun of about 3.0AU, which will be the case in November 2014. After that, the nominal science will be performed as described later in this paper. Nominal end of mission will be end of 2015 at a heliocentric distance of 2 AU postperihelion.

The comet is a comparatively small body with an estimated 2 km radius[4]. In a typical orbit, its gravitational attraction is about the same order of magnitude as the solar and planetary perturbations and the solar radiation pressure. This means that the spacecraft will not fly on Kepler orbits. It will also be difficult to predict the precise position of the spacecraft for more than a few days to weeks in advance. Thus a concept based on e.g. a ‘frozen orbit’, as used in many other planetary missions, cannot be used.

Another obvious issue when preparing a planning concept for a comet is the fact that the comet will change as it gets closer to the sun: It will become more active and additional perturbing forces on the spacecraft due to volatiles emanating from the comet’s nucleus will increase. Also, dust jets may become active on the nucleus which would need to be avoided by the spacecraft.

II. Characteristics of the Rosetta Mission and implications for the Planning Concept

This section describes those aspects of the Rosetta mission that imply requirements on the science planning concept. Each of these aspects is addressed in the description of the science planning concept in the next section. The first subsection deals with the spacecraft and the mission profile, the second with specific aspects from payload instruments, and the third subsection deals with a topic specific to the Rosetta mission, namely the target comet and its environment.

A. Spacecraft Characteristics and Mission Profile

The distance from the Earth (about 3.5 AU at the beginning of routine science planning after delivery of the lander) introduces a non-negligible light-travel time for the TM and TC signals with varying values. At the beginning of the comet science phase this time will be of the order of 60 minutes (two ways) and decreasing towards about 15 minutes at the end of the nominal mission. Due to the nature of the mission with delayed accessibility to the spacecraft, a level of on-board autonomy is in place to execute routine operations and to react to contingency situations. Autonomy both at platform and payload level has been designed to provide an increased level of safety and to execute long periods of operations without ground contact.

Daily telecommunications of the spacecraft will depend on ground station availability during the escort phase, however at least 8 hours daily is expected. Nevertheless, the telemetry bit rate will be limited compared to the on-board data generation rate and should a payload instrument overfill its SSMM allocation, data will be overwritten. Payload data generation rates onboard are highly variable and limited by the downlink availability and/or bit rate. To compensate there is a large on-board data storage capacity and the capability to run parallel recording and dump operations. On payload side, the scientific camera system OSIRIS has the flexibility to select the telemetry that is transferred to the SSMM.

The number of telecommands available to payload operations is limited to the order of 1000 per groundstation coverage period. Efficient commanding in terms of telecommands per operation will be mandatory.

The High-Gain Antenna (HGA) of the spacecraft is steerable. However, the availability of Earth-pointing depends on the position and attitude of the spacecraft and needs to be evaluated in the planning process.

At the beginning of the escort phase, the heliocentric distance will be approximately 3 AU and parallel operations of the payload may be limited by power constraints. The availability of power as a function of heliocentric distance will be approximately known before entry of the spacecraft into deep space hibernation.

During the nominal mission phases the Sun distance will decrease from around 3 AU to 1.24 AU at perihelion. This will impact the thermal environment of the spacecraft as the initial operating temperatures will be very low and will increase as the mission continues. Initially this will call for extended and continues heating requirements from the payload.

Spacecraft attitude is constrained by the requirements of illumination of the solar panels, and solar avoidance requirements of some spacecraft systems (louvers, thrusters) and payload instruments. The planning system needs to make sure that those constraints will not be violated.

The Rosetta mission has a very long development duration. The Announcement of Opportunity was in 1995 and the expected end of the archiving will be after 2015. This calls for accurate knowledge management.

B. Payload Operations Requirements

Principle investigator (PI) teams have developed payload instruments to achieve the mission science objectives. The spacecraft has been developed by industry to transport the payload to the in-situ environments required by the instruments, to provide their resource needs (power, data storage), to ensure safety (automated monitoring) and to facilitate data transfer to and from the instruments.

PI teams will have requirements on when and how to operate their instruments for scientific observations to meet their science objectives. In terms of planning science activities, collaboration with other instruments is necessary both on an operational level, as they share the same platform (s/c pointing requests, interference), and on a scientific level as payload instruments have been selected to obtain complementary scientific data. This calls for facilitating the collaboration and agreement, where needed, between the PI teams.

Most payload instruments will operate in parallel to collect data, perform in-situ analysis and package and distribute data.

C. The comet and its environment

The most peculiar aspect of the Rosetta mission is its operation in the proximity of a small and active body. The most dramatic consequence is limited stability and predictability of the orbit of the spacecraft relative to the comet. The following factors are important:

- Due to the small size of comet 67P/Churyumov-Gerasimenko, the orbit of the spacecraft is disturbed by higher moments of the gravity field of the comet, solar radiation pressure, and gas pressure from cometary activity. Using current best guesses of the parameters involved, at least orbit types are expected to be predictable for extended periods of time (months)[5]. However, some of the parameters involved are uncertain and the planning system needs to be capable of supporting short turn-around times down to a week.
- The cometary dust environment poses potential risks to the spacecraft. Although relative velocities will be low (10s of m/s), large dust particles may damage sensitive spacecraft parts. Small dust particles may cover spacecraft surfaces, and, finally, large numbers of individual dust particles may impact the attitude determination by confusing the star trackers (misidentification as stars). Therefore the spacecraft may not be able to stay close to the comet for extended periods of time, especially close to perihelion. During the routine science phase the dust environment will be relatively well known. However, the planning concept needs to consider the possibility that the available time close to the nucleus may be limited.

The level of activity of the comet needs to be continuously monitored. It is a hazard for the spacecraft on one hand, but also opens opportunities for scientific observation on the other hand. A quick feed-back of observational results into the planning process is mandatory.

The special situation of Rosetta at Comet 67P is also a challenge for risk management. Margins of safety will be put in place to mitigate any risk to the spacecraft due to the limited predictability of the environment. As the Sun is approached and the comet environment becomes more active the hazardous conditions may change more quickly. In turn margins of safety will potentially become more restrictive on spacecraft operations. At the same time, in an environment of limited predictability it is not always possible to base security considerations on worst case assumptions. A conflict of interest can arise when an increasingly active environment is encountered that is of interest for scientific observation but too hazardous for unrestricted spacecraft operations. The planning concept needs to be able to deal with frequent changes in spacecraft constraints.

Mission Science objectives are established and given prioritization by the scientific community for the Rosetta mission to Churyumov-Gerasimenko. As the target comet is relatively undefined and there are many unknowns, the scientific community may revise the priorities at key times as more experience with the comet is gained. The capability to monitor progress or the completions of scientific objectives is paramount to identifying evolving requirements and completing a successful mission. The flexibility to re-address objectives that could not be met for any reason should be in place for this reason.

D. Summary: Requirements on the planning system

- **Orbit planning:** In addition to the usual attitude and operations planning, the planning process for Rosetta requires interfaces for the orbit planning.
- **Flexibility**: The key to successful operation of Rosetta at the comet is flexibility of the planning system
  - The timescale of the planning steps needs to be flexible. The planning system needs to be able to deal with the possibility of knowing the orbit only 10 days in advance with sufficient accuracy to start detailed planning of attitude and operations. At the same time a more typical planning cycle of weeks should be foreseen when possible in terms of orbit predictability.
  - The planning system needs to be able to deal with changes in safety constraints on short notice.
  - In order to timely detect hazards from the changing environment of the comet, to detect new science opportunities, and to monitor the progress of the observations, quick look analysis of results from instruments and feedback into the planning process is necessary.
- **Prioritization:** Apart from scientific criteria, prioritization of instrument operations needs to consider safety of the spacecraft and its payload (e.g. necessity of continous monitoring of the dust flux when close to the nucleus).
- **Resource modeling:** The system needs to be capable of modeling the data volume creation by the instruments and the downlink to Earth. The power consumed by the instruments needs to be predicted as well. Envelopes as used during the cruise phase may be sufficient, depending on confirmation of the estimated power profile. The system needs to monitor the number of telecommands per coverage period.
- **Thermal constraints** as a function of heliocentric distance and, where applicable, attitude, need to be considered.
- **HGA pointing** must be part of attitude planning. Attitude planning needs to include constraints from S/C subsystems and payload systems.

III. Science Planning Concept

The science planning concept is divided into four parts: Section III.A provides a short overview of the planning concept. Section III.B discusses the responsibilities of the different teams involved. Section III.C describes the activities to be performed before the escort phase begins. In section III.D we detail the planning cycle during the routine operations at the comet, section III.5 will discuss deviations from the routine planning. The final part discusses some particular aspects of the planning process.

A. Overview

The planning concept for the Rosetta escort phase is expected to cover approximately 14 months of operations. Given the complexity of operations close to a comet as outlined in the last section, a timely start of the preparation is mandatory.

The first step is creating a science driven baseline plan. This is ongoing with the collection of the science objectives and associated measurements in a Science Themes table. The Science Themes Table will be used as a basis for an overview describing which payload operations will be done in which mission phase and what kind of orbit and which pointing modes are required.

Once all planning tools will be available, the baseline plan will be expanded into and replaced by a more detailed long-term plan. The long-term plan is an orbit, attitude, and operations plan that will be the basis of the actual operational planning cycles. It will be continuously updated based on science objectives (measurements) already achieved, changes in priorities based on new results, and changes to constraints.

The long-term plan is the basis for the actual medium and short-term planning cycle. Orbit, attitude and operations for a time period will be planned during the medium-term planning cycle and fixed in the given order (orbit first, then attitude and then operations). The short-term planning cycle consists of short-term adjustments and go-nogo decisions.

B. Mission Teams & Responsibilities

PI teams:

- Define Science Objectives and associated measurements and constraints for their instruments. Prioritization of those measurements.
- Participate in the development of the long-term plan and provide final approval
- Interact with RSOC during the medium-term and short-term planning
- Monitor instrument health and initiate contingency operations when needed
- Analyze data and provide those results that are relevant for operations planning to RSOC and RMOC
- Update operation requests and constraints when needed
- Representation at the Rosetta Mission Operations Centre during critical phases

Rosetta Science Operations Centre (RSOC), ESAC, Villanueva de la Cañada, Spain:

- Consolidate PI requests first into a baseline plan and then into a long-term plan, taking into account known constraints on orbit and attitude
- Provide constraints on the trajectory to the flight dynamics team
- Drive medium and short term planning, scheduling of attitude and orbit
- Constraint checking (safety and operational constraints)
- Resource checking (power, data volume, number of telecommands)
- Solve conflicts between PI requests in interaction with the PI teams whenever no conflict-free schedule is found
- Support PI teams in the data analysis and feed back relevant results into the planning process
- Representation at the Rosetta Mission Operations Centre during critical phases

Rosetta Mission Operations Centre (RMOC), ESOC, Darmstadt, Germany:

- Plan the spacecraft trajectory based on orbit and attitude constraints provided by RSOC
- Constraint checking (safety constraints).
- Resource checking (power, number of telecommands)
- Send the validated attitude to the spacecraft
- Send the validated telecommands to the spacecraft
- Provide telemetry data to the PI teams and RSOC

C. Pre-Mission Phase Preparation

The following planning phases shall be complete before the routine science phase begins. The 14 months will be broken up into manageable periods so that planning can be performed in a timely manner with all safety measures firmly in place.

1. Baseline Planning

The baseline planning is ongoing. The period covered in the plan is the entire nominal mission phase from after lander delivery to perihelion. The tasks for this period are as follows:

- RMOC, RSOC, and the PI teams agree on a separation of the escort phase into mission phases, based on heliocentric distance and the corresponding expectation for the activity of the comet. Four mission phases were defined in this way.

- For each mission phase, the Science Working Groups of the SWT provide a list of payload operations prioritized according to their importance for the science goals of the mission, represented by the Science Themes.
- The instrument teams provide
    i. For each of their operations, the estimated duration, required resources (power, data volume, number of telecommands), constraints and criteria to be met on e.g. orbit, attitude, or illumination conditions.
    ii. Expected maintenance and calibration requirements
- The flight control team provides:
    i. Available power as a function of heliocentric distance and available data rate as a function of geocentric distance
    ii. Estimated number of telecommands available
    iii. Other operational constraints (e.g. solar pointing constraints) vs. time or heliocentric distance
- The flight dynamics team provides constraints on the trajectory (e.g. distance, relative velocity between spacecraft and comet)
- As output RSOC produces, for each mission phase, the estimated frequency of the most important pointing modes (e.g. track centre, limb pointing) and estimates of available time for different operations using simple example orbits (meaning few changes in orbit per mission phase).

2. Creation and population of an information repository

To allow flexible planning and short turn-around times, most elements of the planning process will be predefined and drawn from an information repository during the actual comet operation phase. It will be started to be filled in during the base line planning and shall be finished before arrival of Rosetta at the comet. The following data will be included in the repository:

- The Operations Requests from the orbiter and lander for all planned operations. The power profile and data rate or date volume information needs to be included as well as constraints on the time of execution (e.g. mission phase, distance from the comet or illumination constraints). The operation requests may contain modifiable parameters (variables) that can be set during the medium and short term planning. The requirement is that the impact of parameter changes on resources (power, data volume) is well understood. Data rate/data volume may depend on the properties of the cometary environment and may need updating based on orbit, attitude, and improved knowledge of the comet.
- Expected pointing definitions. All basic pointing modes should be covered, with modifiable parameters.
- Spacecraft constraints and general constraints on instrument operations. Those constraints should generally be known before arrival at the comet, but will be updated in case the need arises.

3. Long Term Plan (LTP)

The first version of the LTP shall be completed before the first medium term planning cycle begins. This shall be well in advance of the nominal mission phases. The period covered is the entire escort phase from encounter to 2 AU postperihelion. The long-term plan will be regularly updated. It is created in the following steps:

- A trajectory plan is agreed on by all parties, based on the input from the baseline plan.
- For each mission phase, RSOC produces a draft of the long term schedule, or possibly a few alternative suggestions, based on the trajectory, the prioritisation from the baseline plan, the current best comet model, and the information repository. Conflicts are highlighted and subsequently solved by the SWT or by working groups.

4. Phase between end of spacecraft hibernation and lander delivery

This phase is expected to cover the time period from early 2014 to Oct./Nov. 2014. It will be driven by RMOC. The main tasks with respect to the routine phase planning concept are:

- Update of the long-term plan based on improved knowledge of the comet and its environment and on scientific results achieved during this period. Certain science objectives may already be achieved in this phase, rendering some planned operations unnecessary. Other operations may be prompted by those results or change priority.

- Support of the planning of the pre-lander delivery operations with software tools developed for the routine phase, e.g. resource analysis and scheduler.

D. Routine Planning Cycle

Inputs to the planning process will become available at different times. Some will be available well before the nominal phases begin and some will only be available very close to execution time. Some will rely on data from previous observations. The following planning periods are introduced: Baseline planning, Long term planning, Medium term planning and Short term planning. Each planning period is given criteria that determine the duration and the start time of these periods. Criteria are generally the planning time required and the availability of inputs.

The baseline and long term planning were discussed in the previous section and shall be completed before the nominal phases. The long term plan will be updated regularly also during the nominal phases. During medium and short term planning, the spacecraft trajectory will be frozen first, followed by pointing and then by payload operations. Therefore the medium term planning is split accordingly into trajectory (or scenario) planning, pointing and operations. Of course trajectory, pointing, and operations are interdependent and are analyzed simultaneously. The short term planning will generally allow only minor updates to the operations plan.

The duration of the section covered by the medium- and short term planning cycles will vary depending on the availability of inputs and the orbit. Typical durations of the order of a week are envisaged.

Figure 1 gives a high level overview of the elements of the medium and short term planning process during the escort phase. The operational building blocks are stored in the information repository. Based on the long-term plan, RSOC schedules the operations to be run during a given phase. Note that the operations in the database contain orbit and attitude requirements. RSOC iterates with the PI teams and sends a consolidated request to RMOC. The planning system will include attitude and orbit constraints and the request to RMOC should already be conflict free. Following additional checks by RMOC, the operations will be uplinked to the spacecraft. The data received will be made available by RMOC to the PI teams, and, to the extent they are needed for operations planning, to RSOC. The Science Results feed back into the planning system through changes to the comet model and the prioritization of operations.

1. Medium Term Scenario Planning (MTSP)

Each scenario has one MTSP. The MTSP will generally start about 4-6 weeks before the scenario and will be finished 3 weeks before start of the scenario. Should the orbit not be known with sufficient accuracy at that stage, it will continue until the orbit will be known well enough for event driven planning (this means it will be known that certain geometries will be reached within acceptable accuracy, although the time of those events may be uncertain). At the end of the MTSP the spacecraft trajectory for the scenario will be fixed. The following actions are taken during the MTSP:

- Selection of the final S/C trajectory for the scenario. It is based on the long term plan, but potentially modified according to latest knowledge about the cometary environment and on scientific results produced so far. Both, safety considerations and optimization of scientific output are important when fixing the trajectory. Trajectory selection consists of the following steps:
    - Based on the operations foreseen for the scenario, RSOC submits to flight dynamics requirements on the orbit and requirements on the attitude that may be relevant for orbit planning (requirements may include e.g. distance from the comet, availability of landmarks, illumination conditions,…). The requirements submitted by RSOC are the requirements implied by the operations foreseen for the period.
    - Flight dynamics provides one or a few candidate orbits.
    - One of the candidate orbits is selected by RSOC.
- Modifications of the attitude profile and the operations plan. This may include use of different Operations from the data base compared to what is foreseen in the LTP.
- The MTSP phase is the last opportunity for changes in the information repository.

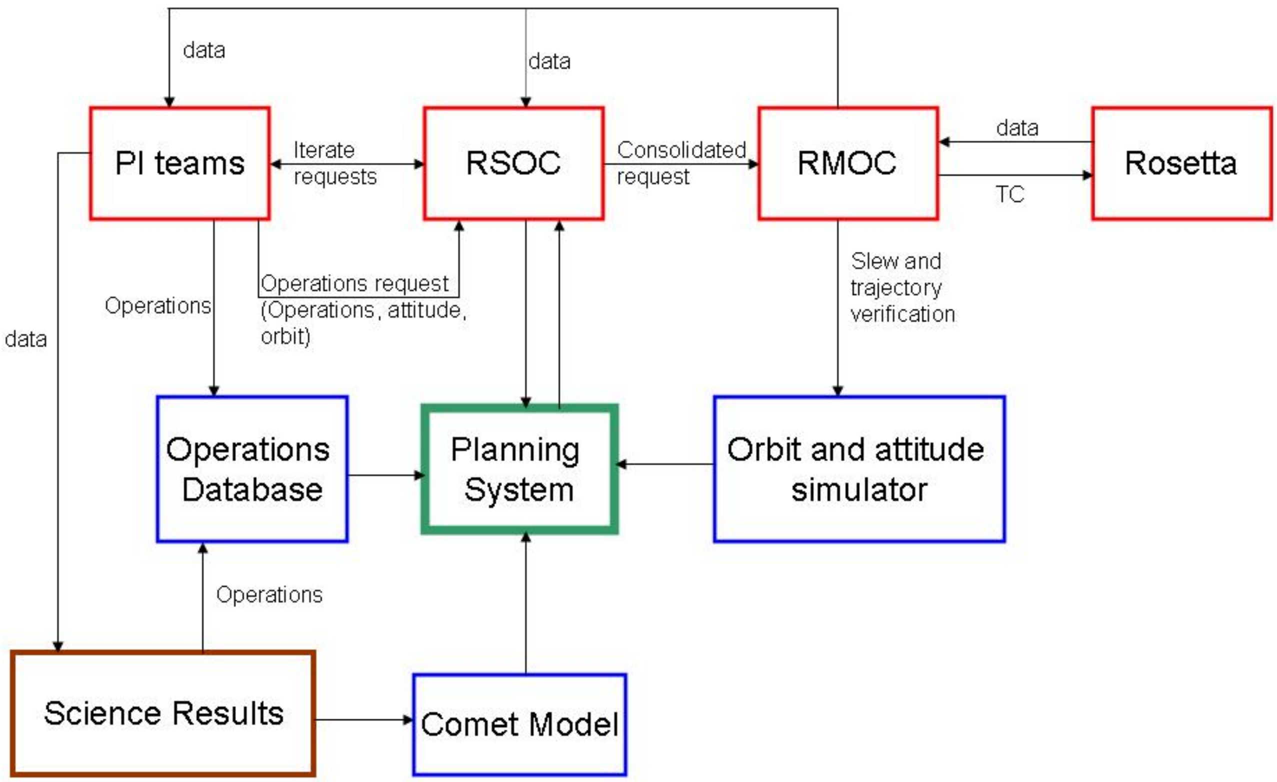

Figure 1. Overview of the operations of Rosetta during the escort phase.

2. Medium Term Pointing and Operations Planning (MTPP)

Each scenario has one MTPP. The MTPP will start after the MTSP (when the orbit has been fixed) and will nominally be finished approximately 2 weeks before start of the scenario. In case the end of the MTSP has to be later due to late availability of orbit information, the MTPP will be shifted, and, if necessary, be shortened accordingly. At the end of the MTPP the attitude profile for the scenario will be fixed. The following actions are taken during the MTPP:

- Selection of the final attitude plan for the scenario, optimizing the scientific return.
- Adopt operations plan to the attitude plan.

3. Medium Term Operations Planning (MTOP)

Each scenario has one MTOP. The Each MTOP will start at the end of the MTPP and be finished about 1 week before start of the scenario. At the end of the MTOP the operations for the scenario will be fixed, with exceptions of parameter changes that have acceptible impact on resources. Actions during the MTOP are:

- Finalisation of operations plan
- Start of processing of plan for submission to the spacecraft.

4. Short Term Planning (STP)

Each scenario has one STP. The STP starts after finalisation of the Medium Term plan, typically about 1 week before start of the scenario. At the end of the Short Term Planning the operations are uploaded to the spacecraft. This will typically be 1-3 days before the scenario will be started.

Generally the plan for the scenario is fixed at the end of the medium term planning. Possible modifications to the operations in the Short Term Planning period are:

- Revise parameters to operations based on latest results about e.g. the cometary environment or the spacecraft orbit. This is only possible if no conflicts are created (due to e.g. increased resource usage).
- Nogo for operations of an instrument in case the instrument team discovers a serious problem.
-

5. Planning Cycles

The duration and timing of the different medium and short term planning phases given here is approximate and may very depending on the requirements of each mission phase.

E. Deviations from the routine planning

It may be necessary to deviate from the routine planning either due to unpredictable changes to the cometary environment or due to anomalies on the spacecraft. This is estimated to happen a few times during the 14 months of routine mission.

In case of a deviation from the plan one or more operation scenarios may be lost. Generally it is not tried to recover lost operational scenarios. However, if high priority operations are lost in an scenario, they may be reintroduced in later scenarios, replacing lower priority operations if necessary.

Below deviations from the planning cycle are discussed, grouped according to the timescale of the required changes:

1. Immediate deviations

Immediate deviations from the routine planning may be necessitated by an outburst of the comet when the spacecraft is close to the nucleus, requiring changes to the orbit as fast as possible, by a spacecraft anomaly, or an anomaly of an instrument (normally affecting operations of that instruments only). In such cases implementation of a safe trajectory and attitude will be necessary as fast as possible (in the “comet driven” case), or the planned trajectory and attitude will not be achieved and operations may be lost for some period of time (spacecraft anomaly case).

In the contingency situation of a sudden change to the orbit the existing attitude and operations planning for the current and the next planning periods may be invalid. If timely interaction between RMOC and RSOC is not feasible for a certain time span within the planning horizon, the operations may be updated and rescheduled by RMOC based on the constraints on attitude and operations and priorities of operations.

Once the spacecraft is safe after such an event, the routine planning is resumed with the begin of the next available scenario, if necessary speeding up the medium term and short term planning by minimizing the modifications performed in each step. Substantial changes to the long-term plan may be required.

2. Short term deviations

In case of an outburst, emergence of a jet, or other sudden changes of 67P, the science output may be substantially increased if the operations can be adapted to that change on a time scale of a few days. This will be achieved using predefined operations: If trajectory changes are required, a previously tested orbit will be used. The required pointing profiles and operations are drawn from the information repository. Note that this may imply development of special operations, e.g. the case of an outburst when building the repository. The plan will be executed once a conflict-free solution is found. In this case fast execution has priority over fine-tuning the operations plan.

3. Medium term deviations

Some cometary events may be predictable for a limited amount of time. A possible example are the “mini outbursts” detected by Deep Impact on Comet 9P/Tempel 1 (Ref. 6). They occurred with some regularity and may be predictable for a few days or weeks. Such events may require changes to the trajectory and/or attitude after the end of the relevant medium term planning periods. Those changes will be implemented the same way as the short-term deviations: By using previously tested trajectories and predefined pointing profiles and operations, and by minimizing iterations on the medium and short-term plan.

F. Special consideration

1. Opportunity Based Scheduling

Scheduling of operations is complex for Rosetta because, contrary to other missions, the spacecraft trajectory is modifiable on relatively short time scales and can be predicted for a limited time only. The planning needs to consider that choices for trajectory and attitude profile depend on one another and that any changes to them require changes to operations. In addition, the operations plan will be continuously changed due to new information about the comet**.**

The high-level outline of the planning system is given in Fig. 2. An opportunity analyzer and a scheduler are used to generate the products required by RMOC from the database inputs and the modules that calculate the various environmental (mostly cometary), spacecraft and payload parameters needed for constraints checking. Some of those modules will be created by RMOC or be based on modules created at RMOC. In the latter case it needs to be made sure that changes to the RMOC modules are implemented in near realtime.

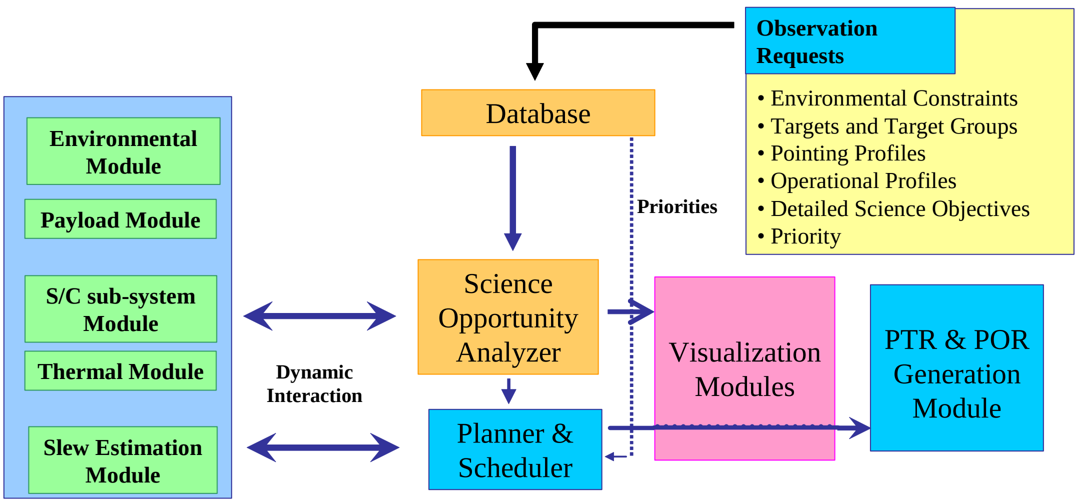

Figure 2. Outline of the planning system

Collected requests shall be scheduled based on opportunities that fit the request criteria. Requested operations will only be scheduled at times where all request criteria are met and all constraints are met. When no opportunities are found for a certain request, either its operational constraints need to be relaxed or the request needs to be dropped. Requests that match the same opportunity but do not match on spacecraft pointing requirements shall be selected based on priority. Different options for spacecraft trajectory and attitude are evaluated according to the opportunities and therefore the scientific output they provide.

Opportunities shall be based on the latest simulation models. Analysis of opportunities shall be rapid to accommodate changes in the environment.

Scheduled operations shall all be traceable back through the selection process.

Constraints shall be revised at key stages based on results from continuous operations. Simulation models shall be updated at key stages based on most current data collected and analysed.

2. Closed Loop Planning Process

The science planning process shall be closed loop so as to effectively measure progress and to capture opportunities. This is schematically indicated in Figs. 1 and 2. The closed loop planning process includes the following steps:

- planning and execution of scenarios.
- download and reduction of relevant spacecraft and payload data.
- progress tracking.
- feed back into the routine planning process.
- detection of new opportunities.

The planning and execution of routine operations are covered in a previous section. Key payload instruments shall be used for continuous surveillance of the comet for safety and opportunity spotting.

Relevant spacecraft and payload data will provide a basis to analyse the expected outcome of planned operations. Collected requests will be cross referenced with this analysis in order to report on operational progress in terms of science objectives. Revision of the routine planning will be supported with the resulting reports.

During the baseline planning the definition of a new opportunity will be established with clear criteria. Relevant data, mainly from payload taking part in surveillance activities, will be selected to measure and detect new opportunities based on criteria established.

3. Payload Resource Management

Payload resource requirements shall be limited by data, power, and telecommand availability profiles. Opportunity based scheduling criteria will rely on accurate prediction of payload resource requirements. Payload resource requirements shall be obtained from the PI teams.

Payload resource usage during flight shall be monitored and compared with prediction to improve prediction in the planning process and to mitigate potential bottlenecks.

There shall be two methods in place to provide predicted payload resource usage as follows: a) modelling based on TeleCommands and TeleCommand Sequences, b) resource profiles provided by payload instrument teams. In both cases payload instrument teams will be the source of the required information.

4. Spacecraft Risk Mitigation

Spacecraft safety constraints will be established by RMOC and will be revised at key stages. Criteria used for enforcing safety margins shall take into account the impact on science in consultation with the science ground segment.

5. Payload Risk Mitigation

Payload risk mitigation will be put in place by applying safety constraints and monitoring payload health. Payload safety constraints will be requested by PI teams and applied by RSOC/RMOC and will be revised at key stages. Criteria used for enforcing safety margins shall take into account the impact on science in consultation with the science ground segment. Payload health will be monitored primarily by RMOC under the requirements of PI teams. This will mean the extraction and evaluation of relevant payload housekeeping data and the application of pre-agreed contingency recovery procedures in case of anomalies. There will be procedures in place to detect, isolate,investigate and recover from anomalous behaviour.

6. Validation & Acceptance

Payload operations requests shall be validated at key stages in the planning process and call for payload instrument team acceptance. The selected trajectory, pointing plan and operations plan will be validated including checks on syntax, consistency, timing, correctness, operational conflicts and constraints against agreed boundaries. The routine and non-routine scenario planning shall be based on validated operations only. Validation processes and responsibilities shall be agreed and documented. Finalised scenario plans will be checked by payload instrument team before execution.

7. Science Ground Segment Performance

The performance of the science ground segment shall be evaluated at key stages on the following indicators:

- Scientific objective progress.
- Flexibility of planning process.
- Speed of planning process.
- Completeness of planning process.
- Alignment of Request to Results.

8. Knowledge Management

All material produced by the SGS from planning activities and results reporting shall be archived as per standard. All data generated by spacecraft and payload shall be archived as per standard.

References

[1]Glassmeier, K. H., Boehnhardt, Koschny, D., Kührt, E., and Richter, I., "The Rosetta Mission: Flying Towards the Origin of the Solar System," *Space Sci. Rev.*, Vol. 128, No. 1 2007, pp. 1-21.

[2]Wirth, K., Küppers, M., Vallat, C., Ashman, M., Schulz, R., and Schwehm, G., "Science Operastions Aspects of the Asteroid Flybys by ESA's Rosetta Spacecraft," *this issue*.

[3]Keller, H. U. et al., "E-Type Asteroid (2867) Steins as Imaged by OSIRIS on Board Rosetta," *Science*, Vol. 327, No. 5962, 2010, pp. 190-193.

[4]Lamy, P., Toth, I., Groussin, O., Jorda, L., Kelley, M. S., and Stansberry, J. A., "Spitzer Space Telescope observations of the nucleus of comet 67P/Churyumov-Gerasimenko", *Astron. Astrophys.*, Vol. 489, No. 2, 2008, pp. 777-785.

[5]Mysen, E., and Aksnes, K., "On the dynamical stability of the Rosetta orbiter.I.", *Astron. Astrophys.*, Vol. 455, No. 3, 2006, pp. 1143-1155.

[6]A'Hearn, M. F., et al., "Deep Impact: Excavating Comet Tempel 1", *Science*, Vol. 310, No. 5746, 2005, pp. 258-264.