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Activity-based Scheduling of Science Campaigns for the Rosetta Orbiter: An Early Report on Operations

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Abstract

Rosetta is an ESA cornerstone mission that will reach the comet 67P/Churyumov-Gerasimenko in August 2014 and will escort the comet for a 1.5 year nominal mission offering the most detailed study of a comet ever undertaken by humankind. The Rosetta orbiter has 11 scientific instruments (4 remote sensing) and the Philae lander to make complementary measurements of the comet nucleus, coma (gas and dust), and surrounding environment.

The ESA Rosetta Science Ground Segment has developed a science planning and scheduling system that includes an automated scheduling capability to assist in developing science plans for the Rosetta Orbiter. While automated scheduling is a small portion of the overall Science Ground Segment (SGS) as well as the overall scheduling system, this paper focuses on the automated and semi-automated scheduling software (called ASPEN-RSSC) and how this software is used. Specifically, the Rosetta mission uses an incremental planning process of successive refinement of the science mission plan beginning with skeleton planning, long term planning, medium term planning, and short term planning. These phases represent the evolution of the science mission plan from one year before execution running through just before execution. We also report on ASPEN-RSSC experience and usage during the pre-landing operations phase thus far.

1 Introduction

Rosetta is an extremely ambitious mission by the European Space Agency [ESA, Factsheet] to conduct the most detailed exploration of a comet ever performed. The Rosetta spacecraft was launched in March 2004 and has circled the sun almost four times in a ten-year journey to comet 67P/Churyumov-Gerasimenko. Its trajectory has included one Mars (2007) and three Earth (2005, 2007, 2009) flybys. Its path has also included a flyby of the Steins (2008) and Lutetia (2010) asteroids.

The Rosetta spacecraft was approximately 3000kg at launch and is approximately 2.8 x 2.1 x 2.0 meters with two 14 m long solar panels with a total of 64 meters squared of solar panel area for power generation.

Science planning for the Rosetta mission is extremely complex with each of the eleven science instruments conducting multiple science campaigns and presenting numerous operational constraints on the spacecraft to achieve their science measurement including geometry, illumination, position, spacecraft pointing, instrument mode, timing, and observation cadence. Because of the challenges in effectively planning science instrument operations, ESA has a highly skilled team of liaison scientists and instrument operations engineers who work with the instrument teams using the SGS to develop science plans for the Rosetta mission.

In order to streamline science planning during operations, significant elements of the science operations are pre-planned as part of a skeleton plan. Once a skeleton plan is formed, as it approaches operations it is systematically refined and detailed. Depending on the mission phase, portions of the mission are broken down into 16 week duration Long Term Plans (LTP), 4 week long Medium Term Plans (MTP), or 1 week long Short term plans (STP).

The Rosetta mission has developed an automated science scheduling capability to support both skeleton plan development and operational plan refinement. While this scheduling system, called the Rosetta SGS Scheduling Component (RSSC) is but one part of the overall Science Ground Segment, this paper focuses on the RSSC because the target audience for this paper is the space automation community. Because the RSSC software at its core is an adaptation of the ASPEN automated scheduling and planning engine [Chien et al. 2000] we refer to the adapted/built system as ASPEN-RSSC. Readers interested in other components of the SGS are directed to other papers.

In the remainder of this paper: (1) we describe the overall Rosetta Science Planning flow, (2) we describe the wide range of constraints influencing the Rosetta Orbiter planning process; (3) we describe the scheduling algorithm used by ASPEN-RSSC; and (4) we describe early experiences in usage of ASPEN-RSSC.

2 Rosetta Science Planning

Rosetta science planning proceeds by successive refinement of an abstract science plan, refining the plan and detailing the spacecraft observations and spacecraft pointing successively through a number of planning phases: skeleton planning, long term planning, medium term planning, and short term planning.

Skeleton Plan Generation

Skeleton plan generations involves considering a reference spacecraft trajectory in the context of specific spacecraft and comet conditions, and science priorities. From the perspective of automated scheduling, required inputs include: a spacecraft trajectory, spacecraft state, exogenous conditions (such as downlinks), and science campaigns with priorities. The scheduler can be used by the mission science team to enhance exploration of possible science plans by repeatedly running the scheduler with variations of trajectory, exogenous conditions, and science campaigns. Initial skeleton planning is performed in a time-based excel spreadsheet format in which high-level allocations of the mission and pointings are performed at the 6 hour block level. At this phase of mission planning precise timing information is not used and engineering activities are only coarsely modeled. High-level resource allocations (pointing time, data volume) are mostly explored. Skeleton planning is under way for much of the escort phase Rosetta activity (e.g. November 2014 and onward).

Long Term Planning

At the Long term planning level (LTP) the skeleton plan allocations are refined more concretely using the ASPEN-RSSC planner. At this point, a detailed plan of engineering activities and downlink schedule are available. The principal purpose of the LTP process is to verify that the planned trajectory enables the primary operational observations (required for lander delivery) and prime (high priority) science are achievable with the chosen trajectory. While ASPEN-RSSC can model at a detailed level, at this phase only abstract spacecraft pointings are available and in some cases detailed observations are also not yet defined. Thus, in this phase ASPEN-RSSC may produce a less detailed pointing plan or activity plan.

Medium Term Planning

In medium term planning (MTP) the observations and pointing of the long term are successively refined. In the early phases of MTP, ASPEN-RSSC is used for rapid development of the observation plan but then the ASPEN-RSSC plan is used to generate input products and plan for the Mapping and Planning Payload Science (MAPPS) planning system which is used for the majority of the MTP process as well as short term planning (see below). While ASPEN facilitates automatic generation of Rosetta Science plans and rapid modification of the plan while maintaining adherence to numerous operations constraints, MAPPS is used for the more detailed science planning, constraint checking, and pointing planning. At the exit of MTP the detailed pointing timeline for the mission segment is frozen and in many cases the actual sequencing of the instruments may be determined.

Short Term Planning

In short term planning the detailed instrument timelines (ITL's) are completed. The ITL's are the command sequences for the science payload (instruments) which are an end product of the Rosetta Science Ground System (RSGS). The ITL's are the lowest level format of the Payload Operations Request (POR) that go along with the Pointing Timeline Request (PTR).

3 Rosetta Orbiter Scheduling Constraints

In Rosetta science planning there are a significant number of constraints and preferences that must be accommodated in generating science instrument schedules. In this section we describe a number of these constraints and how they are handled.

Science Campaign Definition

Rosetta science is organized into a number of science themes relating to the scientific questions to be answered by science measurements/observations. Science campaigns are sets of observations that are directed at collecting data to enable the science team to answer these questions and refine relevant theories and models.

Three primary structures exist for scheduling unit observations. “Repeat” requires scheduling of an observation (or set of observations) a number of times with temporal relationships among adjacent observations. “Repeat/insert while obs/window” enables scheduling of observations while a condition is met, such as a geometric configuration (observation opportunity) or concurrent with another observation. “Start/end when Start/end” enables scheduling of one type of observation with a defined temporal relation to a different type of observation.

Another complexity in science campaigns is campaign expansion into schedulable observations. For example, a science campaign may be to map the surface of the nucleus of the comet at a pre-specified spatial resolution, at two varying illumination conditions. The spatial coverage may be represented by expanding the campaign to replicate over a list of point targets and restriction on the distance to the comet. The iteration over the varying illumination conditions is handled by expansion of the previous target set replicating a request for each illumination condition. In general, these expansions are handled by replicating the observation requests over all of the point instances and the cross product of the applicable conditions. This results in an exhaustive enumeration of the observation requests that is then input to the scheduler.

Monitoring campaigns are somewhat different. These campaigns are active over extended periods of time and intend to achieve a specified duration level. Monitoring campaigns may be interrupted to acquire competing observations that have incompatible pointing or state constraints. Monitoring campaigns are generally scheduled around conflicting unit observations but may require search (generally in the placement of conflicting observations) to satisfy the underlying monitoring campaign.

A typical science campaign definition would specify a type of observation to be acquired with a specified cadence (e.g. perform 20-30 Osiris imaging activities of Type Y roughly every 18-28 hours). More complex campaigns might specify multiple observation types with constraints linking the observations (e.g. type A followed by a type B 6-8 hours later). Campaigns can also allow for nesting of constraints (e.g. schedule every 6-8 days a sequence of Alice observations of Type X, where each sequence is 4-6 observations 45-70 minutes apart). Campaign definitions assert constraints to specialize observations (e.g. to set parameters) or constraints in between observations (e.g. temporal spacing, count). Constraints from observation types are represented in the Observation definition below.

In current ASPEN-RSSC usage to date, several patterns of campaign structures have emerged as commonly used. Fill campaigns are used to allocate segments of the schedule to near continuous coverage. Three instruments ALICE (not an acronym), Microwave Instrument for the Rosetta Orbiter (MIRO), and Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) all commonly fill segments of the schedule allocated at skeleton planning level. ASPEN-RSSC then fills the allocated times with the appropriate observation types but enforcing operations constraints that sometimes prevent complete coverage.

Repeat with inner and outer structure is commonly used to schedule observations for the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) instrument, which correspond to a grouping of observations, repeated to achieve some coverage goal, such as mapping of the entire surface of the nucleus (as best possible) by observing with a pre-specified cadence over one comet nucleus rotation (estimated to be 12 hours and 43 minutes). For example, an OSIRIS observation might take 20 minutes and be repeated at each of 9 stations over one comet nucleus rotation. This grouping might be requested to repeat once per week. Simple periodic observations are also commonplace, such as an instrument calibration desired to repeat every 2 weeks. Another observation construct is a layered set of fills. In this structure an instrument might request in order mode A, then Mode B, then Mode C, where A requires the most power or data volume, B less power or data volume, and C still less power or data volume. The intent here is to schedule mode A whenever possible, but when power or data volume does not permit to next try to schedule mode B, when that fails mode C.

Observation Definition

An observation definition specifies a type of measurement to be acquired by a science instrument. It may specify pointing requirements, durations, observation parameters (e.g. integration times), geometric, spatial, and illumination constraints, and operations sequence constraints. In some cases a complex observation (e.g. raster or mosaic) may be defined as a single complex observation. Because some of the dimensions of the raster (e.g. spacing between images) may be defined in reference frames other than spacecraft inertial, the requisite slews may vary based on distance to target. Indeed the slews may not be feasible in certain configurations. This complicates the scheduling as key parameters of the complex observation (e.g. duration, temporal spacing of images) may vary based on when the observation is scheduled.

Sequence

Observations can specify instrument sequences where each sequence is a series of mode transitions required to perform observations. These sequences are often time relative and parameter dependent. For example, each downlink activity has a com_in mode, then a packet store dump period, then a com_out mode. The instruments modes also define the resource usages of the instrument that typically include power, data volume, and data rate but may include other more complex constraints.

Windows of Opportunity

For efficiency reasons for each class of observation, the non-pointing geometric constraints are pre-computed prior to scheduling. Because all non-pointing geometric constraints are defined by the target of interest and trajectory, they can be correctly computed independent of the spacecraft mode, pointing, etc. Common examples of these constraints are distance to target e.g. “when the spacecraft is within 75km of the nucleus” or angles e.g. “solar zenith angle is 30 degrees or more” or “emission angle is less than 45 degrees”.

As we have generated operations plans for the pre-landing phase, it has become common to merge all of the known constraints into the windows of opportunity (WoO), including skeleton plan allocated intervals. In this way, the WoO can be considered an arbitrary constraint on activities, such that the activities must be constrained to occur within the WoO time interval.

Spacecraft State and Resources

State and resource constraints include the instrument and observation constraints described above (modes, power, data volume, etc.). In rare cases instrument modes or observations may have constraints on other instruments or spacecraft subsystems (e.g. Instrument 1 Observation Z requires that Instrument 2 be OFF). These constraints are generally directly representable within the ASPEN modeling language so require minimal adaptation effort.

Pointing and Slewing

Many remote sensing observations have a required instrument pointing. For example, an observation might require that the Osiris instrument boresight be pointed at the point on the surface of the comet nucleus being observed. Observation pointings can be achieved as “prime” or “rider”. Prime means that the observation is dictating the pointing of the spacecraft. Specifically, at some point in time prior to the prime observation, the spacecraft is slewed to achieve the pointing, then the pointing is maintained throughout the observation, and later the spacecraft is slewed to the pointing needed for the next observation (or back to a designated default pointing). Observations can also be achieved as “rider” observations. In this case it is determined that the pointing required by a prime observation is also compatible with a secondary observation. For example while observing a point target with instrument A, imagery with instrument B can be acquired as part of a mapping campaign. Even in this case the presence of the rider may introduce constraints (e.g. the rider may require a longer duration pointing).

The scheduling of observations with significant slewing is an item of considerable concern. In general, the Rosetta spacecraft has a semi default pointing strategy to have the +Z deck pointed at the nadir point of the comet. The remote sensing instruments are generally aligned with the +Z deck so that this pointing is coarsely maintained when the remote sensing images are imaging the nucleus or near the nucleus. However extended scans away from this pointing need to be carefully scheduled. The Alice instrument will be performing periodic series of scans that coarsely cover both axes away from the comet for extended periods of time (up to 12 hours). The Miro instrument performs similar scans along both axes away form the comet. The scheduling of these Alice and Miro scans away from the comet can be critical as Rosetta slews can be quite time consuming (e.g. 20s per degree of slew).

The slewing and pointing of the spacecraft also significantly impacts in-situ, monitoring measurements. The spacecraft is also designed so that the default pointing (Z deck at nadir) optimizes certain in-situ measurements. This is especially important when Rosetta is near the comet as these are the best chances to measure due to increased gas density. Therefore there is a huge incentive to not point away from Z-deck at nadir when the spacecraft is near the comet.

ASPEN-RSSC does not directly reason about pointing and slewing but rather relies on a specialized reasoning planner developed by ESA/ESTEC called the Attitude Generator Module (AGM). Each time ASPEN-RSSC attempts to change the current pointing plan (either to hold pointing, slew to a pointing, or modify a slew), it consults the AGM. The AGM returns the feasibility of the requested change along with exact pointing and slewing times. For example, if ASPEN-RSSC wishes to try to insert a new observation, it might require that a new pointing be inserted into the plan. As part of this change, there might be several slews and new pointings required. The AGM returns detailed information on these pointings and slews (e.g. start and end times). Additionally, the AGM must check and enforce several pointing related constraints. For example, certain instruments must keep their boresights away from bright objects such as the sun, but may close instrument covers to enable such pointing. As another example, certain portions of the spacecraft have thermal illumination constraints (e.g. they may not hold certain types of pointings for greater than a specified duration, and if entering such a zone, after leaving may not re-enter for a keepout time duration). The AGM implements these constraints and reports them back to ASPEN-RSSC for enforcement.

Engineering Activities

Rosetta also has regular engineering activities that affect science operations. Rosetta will have regular orbit correction maneuvers (OCM) to maintain a stable, predictable trajectory as planned. Immediately after a TCM the positional uncertainty of the spacecraft is at its worst. Rosetta will also have regular reaction wheel off loading (WOL) activities. During TCM and WOL activities few science activities are possible. Rosetta will also have navigation imaging activities. During these times the navigation cameras must be pointed at the comet nucleus. This constrains the pointing of the spacecraft not only during the activities but effectively before and after due to slewing times. Regularly scheduled downlinks do not significantly impact science operations because Rosetta has a gimballed high gain antenna.

Certain engineering activities require that science instruments not be in a high voltage (HV) mode. When scheduling science activities, engineering activities that have such constraints have already been scheduled. Therefore ASPEN-RSSC must either schedule these observations to avoid the engineering activities or simply suspend the activities during the appropriate periods.

ALICE and OSIRIS science instruments must also avoid contamination from thruster firings. As such these instruments must have instrument covers closed (preventing science activities) during such engineering activities (OCM, WOL, and WMNV). In the case of ALICE the instrument cannot be use for 30 minutes after the completion of such an activity

Onboard Storage and Data Management

All Rosetta science data must be acquired and stored onboard temporarily for eventual downlink to ground stations. In some cases, instruments have buffers for temporary data storage. Eventually the data is transferred to the central data recorder that is pre-partitioned into instrument spaces called packet stores. Part of the science scheduling process is the management of the data storage to enable the large number of science observations without losing data due to limited onboard storage and inability to downlink. Onboard, Rosetta can be commanded to assign priorities and maximum end times to each packet store dump during a downlink. Packet stores assigned the same priority will be downlinked in a round-robin fashion. These onboard capabilities enable more sophisticated scheduling strategies to be used to accommodate the varying demands on the packet stores.

Because Rosetta receives near continuous coverage from ground stations (18 hours coverage by 3 ground stations out of every 24 hours is common), the common modeling abstraction that downlinks are instantaneous cannot be used for Rosetta downlink scheduling. As part of its scheduling, ASPEN-RSSC generates a “dump” schedule, which indicates exactly when during each downlink each instrument’s packet store is downlinked and how much data is downlinked.

4 The ASPEN-RSSC Scheduling Algorithm

RSSC is implemented using an adaptation of the ASPEN scheduling framework [Rabideau et al. 1999, Chien et al. 2000]. RSSC ingests an XML formatted set of scheduling rules, science campaigns, observation definitions, observation opportunities, etc. and from this automatically generates an ASPEN adaptation for scheduling. This means that changes in campaign, pointing, observation, and other constraints can be made directly in Rosetta project systems and be automatically reflected in the ASPEN adaptation.

ASPEN-RSSC currently uses a constructive, priority-first scheduling algorithm to generate schedules. In this algorithm, campaigns are scheduled in priority first order. Within each campaign, each scheduling rule is also executed in priority order. Before scheduling each rule, adjustments are made to the packet store dump schedule in a way that results in more available space in the packet store for the instrument that will be schedule by the rule. For example, if ALICE observations are requested by the rule, extra dump time is allocated to the ALICE packet store without overflowing other packet stores. In addition, an initial search is performed for the type of observation being scheduled by the rule to pre-select valid start times that best match the preferred separations for *all* observations being requested by the rule. For example, if a rule requests a group of five OSIRIS observations every two days for a ten days, the scheduler searchers for valid start times for all 25 observations that satisfy intra- and inter-group separations, and minimizing the difference from preferred separations. However, because each observation changes the schedule in complex ways (e.g. resources), valid intervals are re-computed for each new observation and the pre-selected start time is used when available.

When scheduling each observation ASPEN-RSSC computes all valid constraint intervals as indicated below:

1. campaign interval
2. separation from other observations as specified by the scheduling rule
3. windows of opportunity
4. instrument, subsystem, and mechanism mode constraints
5. prime and rider attitude availability
6. availability of resource packet stores (e.g. data storage)
7. data transfer rate constraints
8. power

When computing the above intervals, ASPEN-RSSC computes valid intervals even where prior constraints have ruled out observation times. While this decreases the efficiency of the scheduler, it increases the utility of this constraint information that is also used to manually analyse the results of the automated scheduler in working towards a feasible plan.

5 Rosetta and ASPEN-RSSC Status

The RSSC scheduler has been under development since Spring 2011. More recently a series of test integrations in to the Science Ground Segment have occurred (June 2012, November 2012, March 2013) with major integration completing in the Summer of 2013. A more in depth test occurred in November 2013 which identified major areas of work for top prioritization.

The Rosetta orbiter successfully exited hibernation in January 2014. The first two months of post hibernation operations involved checking out spacecraft status post hibernation and commissioning the spacecraft. The next two months of operations (MTP 1 and 2, from mid-March 2014 to 7 May 2014 are payload commissioning, e.g. checkout of the instruments). Following these are planning MTPs 3 and higher. Planning for the period MTP 3 began in January and proceeded directly with MAPPS. MTP 4, 5, and 6 were planned in ASPEN, with a transition to MAPPS at or slightly after the planning periods entered Medium Term planning (~ 2 weeks after MTP kickoff). On 30 April 2014 as this paper goes to press MTP6 is in the Medium Term Planning phase.

MTP’s 4, 5, and 6 are of dramatically increasing complexity as the observation demands are increasing as the spacecraft begins full operations and approaches the comet C-G.

Simultaneously, ASPEN-RSSC is also being used to support Skeleton and Long Term planning for escort phase plans LTP4 (MTP 10,11,12,13) and LTP 5 (MTP 14,15,16,17), with a current emphasis on the High Comet Activity cases.

The current MTP6 plan contains 58 scheduling campaigns, 2119 observations (including engineering activities), and 2130 spacecraft pointings and slews. This plan requires 50-70 minutes to generate a plan with a single run of the greedy heuristic scheduler.

6 Related Work

Many scheduling systems have been applied to space mission operations (for a more thorough survey see [Chien et al. 2012]). In general, ASPEN-RSSC is differentiated from the systems below in that: (a) the very large number of diverse science campaigns represented in RSSC and (b) because Rosetta is essentially a series of flybys a wide range of geometric constraints must be considered across science campaigns (Cassini is the closest similar mission).

The SPIKE system is used in several mission including Hubble Space Telescope [Johnston et al. 1993], FUSE [Calvani et al. 2004], Chandra, Subaru [Sasaki et al. 2004], and Spitzer [Kramer 2000].

The MEXAR2 and RAXEM systems are used in Mars Express operations [Cesta et al. 2007, Cesta et al. 2008].

For surface operations, the MAPGEN [Bresina et al. 2005] mixed initiative planning system is used to plan operations for the Spirit and Opportunity rovers at Mars.

ASPEN has been used for a number of missions. The ASPEN-MAMM system was used to plan the Modified Antarctic Mapping Mission (MAMM) on Radarsat [Smith et al. 2002]. ASPEN is also used for Earth Observing One Operations (flight and ground) [Chien et al. 2010]. ASPEN was also used for the Orbital Express mission [Chouinard et al. 2008]. ASPEN is also used for ground and flight operations of the IPEX cubesat mission [Chien et al. 2014]

The Flexplan system is currently in use for operations of the EPS Eumetsat, SMOS [Tejo et al 2007] Lunar Reconnaissance Orbiter (LRO).

The TerraSAR-X/TanDEM-X Mission Planning System, uses GSOC's Pinta/Plato scheduling applications [Geyer et al. 2011].

Of particular note is [Simonin et al. 2012] which describes a constraint programming approach to modelling operations for the Philae Lander portion of the Rosetta mission. Their work focuses on the data management aspect of the lander operations. While RSSC must handle orbiter data management (e.g. data acquisition, onboard storage, and subsequent downlink to terrestrial ground stations), orbiter data management does not play a central role in Rosetta Orbiter science planning operations.

7 Future Work, and Conclusions

We have described an automated scheduling system ASPEN-RSSC designed to support Rosetta Science Planning as part of the ESAC led Rosetta Science Ground Segment (SGS). This scheduler is in operational usage to generate pre-landing and escort phase plans for skeleton, long-term planning, and medium term planning phases of Rosetta Orbiter operations.

We then described the classes of constraints represented in the system. Next, we described the current search methods being used and some of the constraint and comparison analysis methods currently implemented. Finally we described the current status of the system and plans leading up to comet encounter operations.

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