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Activity-Based Scheduling of Science Campaigns for the Rosetta Orbiter

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Abstract

Rosetta is a European Space Agency (ESA) cornerstone mission that entered orbit around 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 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.

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.

Once a long term 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).

This paper focuses on the RSSC because the target audience for this paper is the artificial intelligence 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.

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: long term planning, medium term planning, and short term planning.

Long Term Planning – Skeleton Refinement

At the Long term planning level (LTP) first the trajectory that the spacecraft will fly is determined. Once the trajectory is determined, observation planning begins in an excel spreadsheet. When this plan is relatively solid, the plan is translated into the ASPEN-RSSC planner. At this point, a detailed plan of engineering activities and downlink schedule are available. 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 may be 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 (SGS). 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.

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.

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.

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.).

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 uses a heuristic downlink scheduler DALLOC [Rabideau et al. 2014] that 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.

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

- campaign interval
- separation from other observations as specified by the scheduling rule
- windows of opportunity
- instrument, subsystem, and mechanism mode constraints
- prime and rider attitude availability
- availability of resource packet stores (e.g. data storage)
- data transfer rate constraints
- 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.

ASPEN-RSSC is generally able to find solutions performing very little search. The typical area where search is performed is in placement of groupings of observations (e.g. for multiple groupings of 12 periodic Osiris observations). In placing these sets of observations it is difficult to predetermine the best solutions in terms of

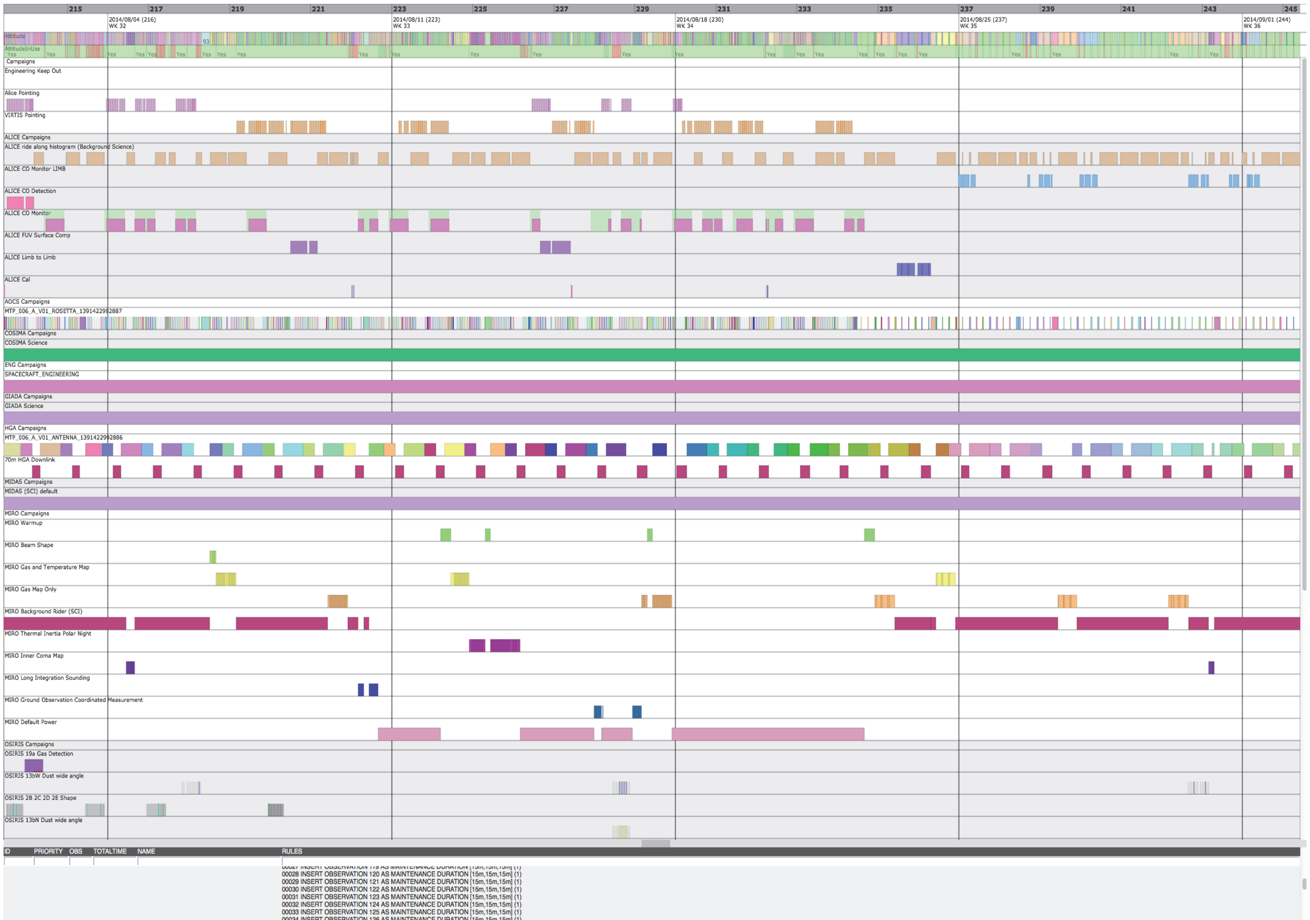

Figure 1: MTP 006 01 Aug – 01 Sep 2014: 32 days, 2027 observations, 2160 pointings and slews, 63 science campaigns, 10,000's constraints checked and over 1400 downlink dumps

spacing of the observations with engineering avoidance intervals and other state and resource constraints.

ASPEN-RSSC has also been used to asses schedulability of observations. For a given observation design, ASPEN-RSSC can be run with empty or partially full plans to assess how hard it would be to schedule a science campaign/observation under design.

A significant utility of ASPEN-RSSC is in providing valid constraint windows for each constraints type for each observation. In this way ASPEN-RSSC can be viewed as computing constraints to assist in semi-automated scheduling and observation design.

5 Rosetta and ASPEN-RSSC Status

The Rosetta orbiter successfully exited hibernation in January 2014. After spacecraft and instrument checkout (MTP 1-3), ASPEN has been used continuously to take early excel science plans and constraint check them and to product detailed iputs for MAPPS.

In particular, the MTP's just before landing delivery (MTP 8-9) involved carrying multiple trajectory contingencies and late breaking planning for which ASPEN proved useful. After the Philae lander was delivered in November 2014 / MTP 9, the escort phase of the Rosetta mission commenced, with science planning for two cotingencies: Low and High comet activity. As this paper goes to press in April 2015, MTP 17 and 18 are in work in RSSC-ASPEN.

As an exmaple of MTP plan size, the MTP6 plan contains 58 scheduling campaigns, 2119 observations (including engineering activities), and 2130 spacecraft pointings and slews. An MTP typically takes 20 minutes minutes to generate a plan with a single run of the greedy heuristic scheduler. Figure 1 shows the screen snapshot of MTP6 under development. Each row represents a science campaign where the blocks in that row indicate observations satisfying that science campaign.

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

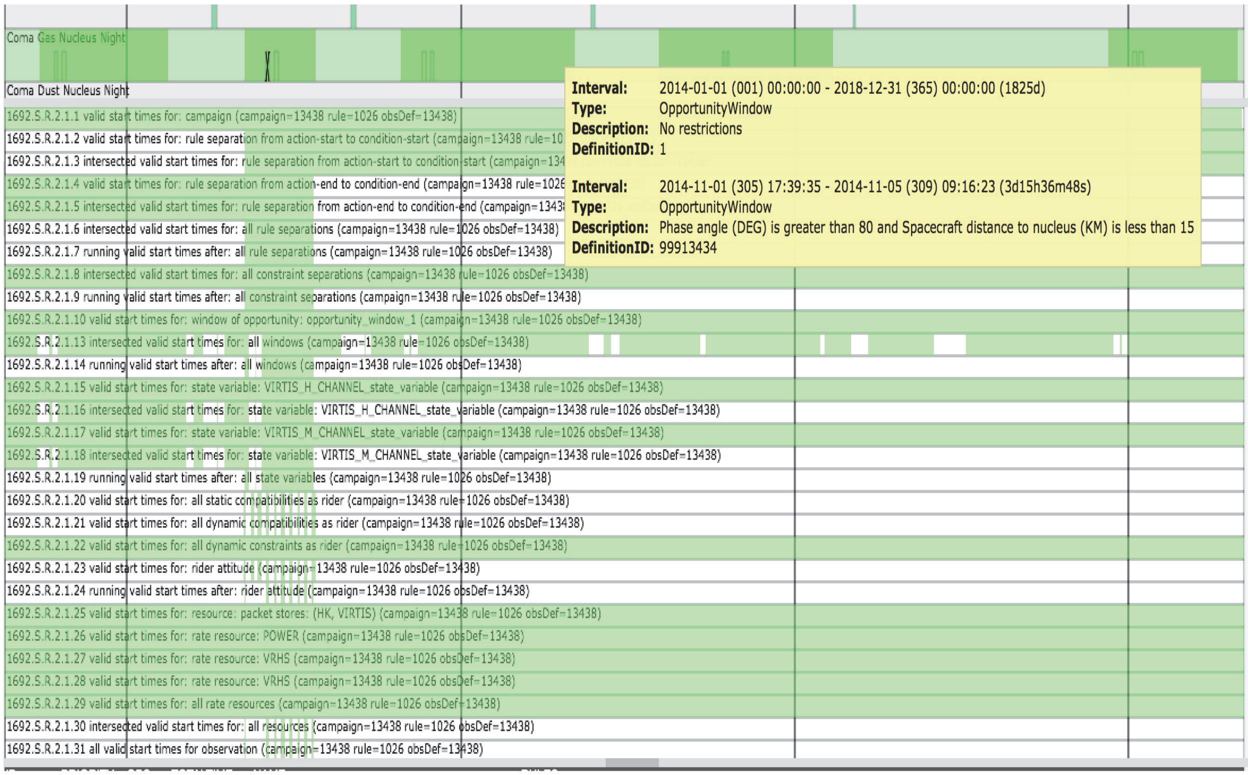

Figure 2: Constraint windows for Virtis Coma Gas Night Landing Site Observation from MTP 9

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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