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Scheduling Science Campaigns for the Rosetta Mission: A Preliminary Report

Steve Chien[1], Gregg Rabideau[1], Daniel Tran[1],
Federico Nespoli[2], David Frew[2], Harold Metselaar[2], Manuel Fernandez [2],
Michael Kueppers[2], Laurence O'Rourke[2]

(1) Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA, 91109-8099, USA, Email: {firstname.lastname}@jpl.nasa.gov

(2) European Space Astronomy Center, European Space Agency, Villaneuve de la Canada, Spain,
Email:{fnespoli, dfrew,hmetselaar, manuel.a.fernandez, Michael.kueppers}@sciops.esa.int, lorourke@esa.int

Abstract

Rosetta is an ESA cornerstone mission that will reach the comet 67P/Churyumov-Gerasimenko in 2014 and will escort the comet for approximately 1 year 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 is developing a science planning and scheduling system that includes an automated scheduling capability to assist in developing science plans for the Rosetta Orbiter. While automation 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 and process.

Prior to arrival at the comet, the Rosetta mission is developing skeleton plans, which are pre-developed plans to conduct sets of measurement campaigns. Automated planning is being developed to support the skeleton planning process by generating plans for given trajectories and science campaigns.

During encounter operations, segments of the skeleton plan, referred to as "bones," will be refined and possibly swapped (for different bone segments). The plan segments will be refined and made operational as part of a long term planning process. Subsequent adaptation as additional information becomes available and earlier observations of the comet will alter science measurement priorities. When these plans are made operational, automated planning will assist the science planning team in adapting and adjusting science plans. In this usage, the automated science planner can be used to evaluate alternative trades by changing the science campaign and observation priorities, constraints, and parameters and generating alternate plans.

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 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.

Portions of this work were carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

In order to smooth science planning during operations, significant elements of the science operations are pre-planned by derivation of so called bones of the skeleton plan. In effect, a bone plan is a segment of science plan that is pre-derived for a specific context (e.g. operations and science phase of the missions). By pre-planning a range of likely contingencies in advance it is expected that a significant portion of escort operations will be adapting already developed and checked plans rather than constructing and vetting plans from scratch. However this strategy requires the pre-generation of the skeleton bones.

During escort operations, the current baseline plan will be modified and adapted to science, comet, and spacecraft conditions. In some cases this may result in significant modifications to the plan. Because this is the first extended mission to a comet, there is much to be learned about the dynamic cometary environment. Therefore the science planning team must be prepared for the possibility that previously developed plans will have to be significantly modified.

The overall science planning process involves managing significant planning related information to support the planning process. For example, ESA is developing the Observation Manager (OBM) software to enable development and storage of science campaigns, observations, and scheduling rules and constraints. Additionally, campaign management and tracking is required to maintain an overall situational awareness of how past, current, and planned observations will and will not satisfy requirements for science campaigns. Additionally, the SGS team is leading the development of the pointing, slewing, and simulation capabilities for the SGS.

The Rosetta mission is developing 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 of the target audience. Readers interested in other components of the SGS are directed to other papers.

In the remainder of this paper we first describe the two operational usages of automated science planning: (1) skeleton plan generation and (2) refinement of plans as they progress through long term planning, medium term planning, and short term planning. We then briefly survey some of the challenges in automating Rosetta science planning. Finally we describe the current state of the implementation of the automated scheduling component of the Rosetta SGS.

Rosetta Science Planning

Rosetta science planning can be broken into two types of planning: (1) skeleton plan generation and (2) operational plan development.

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, an input 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.

Operational Planning

In operational planning, a reference science plan already exists as s proposed bone from the skeleton plan. As this plan progresses from the long term planning cycle to the medium term and short term planning cycle it is adapted based on updates to starting conditions, exogenous events, spacecraft state, and changing science priorities. In this context automated scheduling accepts and input schedule and uses it as a guide to generate a new schedule accommodating input updates as will occur during operations. As a schedule progress closer to execution, certain aspects of the schedule become harder or impossible to change. At a relatively early phase the trajectory is frozen. Next the rough spacecraft pointing is frozen, only allowing for minor changes to reflect navigation updates. Finally, observation activities themselves are frozen only allowing minor parameter changes.

Scheduling Constraints

In Rosetta science planning there are a significant number of constraints and preferences that must be accommodating 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 while repetition” 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 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. A followed by a 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 a 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. 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. Most commonly Rosetta models low, average, and high rates for each of thee quantities and separates housekeeping (engineering) and science data rates and also applies defined compression rates when applicable. However as we move closer to primary operations these models are being significantly augmented to increase model accuracy.

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”.

Spacecraft State and Resources

These 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 adapatation 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 and that some point in time prior to the observation the spacecraft is slewed to achieve the pointing, the pointing is maintained throughout the observation, and later the spacecraft is slewed to the pointing needed for the next observation. 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, acquire imagery with instrument B 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 the 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.

Engineering Activities

Rosetta also has regular engineering activities that affect science operations. Rosetta will have regular trajectory correction maneuvers (TCM) 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 constraints 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.

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. 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. Like many spacecraft, Rosetta allows a single pass through all buffers per downlink, with a variable time/data allocation per downlink, and variable ordering per downlink.

Current Scheduling Algorithm for Skeleton Planning

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.

RSSC currently uses a constructive, priority-first scheduling algorithm to support skeleton plan development. In this algorithm, each science campaign has a fixed priority for minimum, preferred, and maximum fulfilment levels. The RSSC scheduler searches to satisfy each of these levels in turn without revisiting the selections from the earlier (higher priority) scheduling operations.

Within each of these scheduler iterations, the scheduler attempts to increase the fulfilment level of a science campaign as defined. This continues until no more requests exist.

Within each tier for each science campaign considerable search exists. The search tree explored by the scheduler is shown below in Figure 1.

The principal focus thus far has been on skeleton planning in the context of an icosahedral trajectory of 8 weeks in duration in 2015. For this specific skeleton planning problem there are approximately 50 campaigns and over 300 scheduled observations.

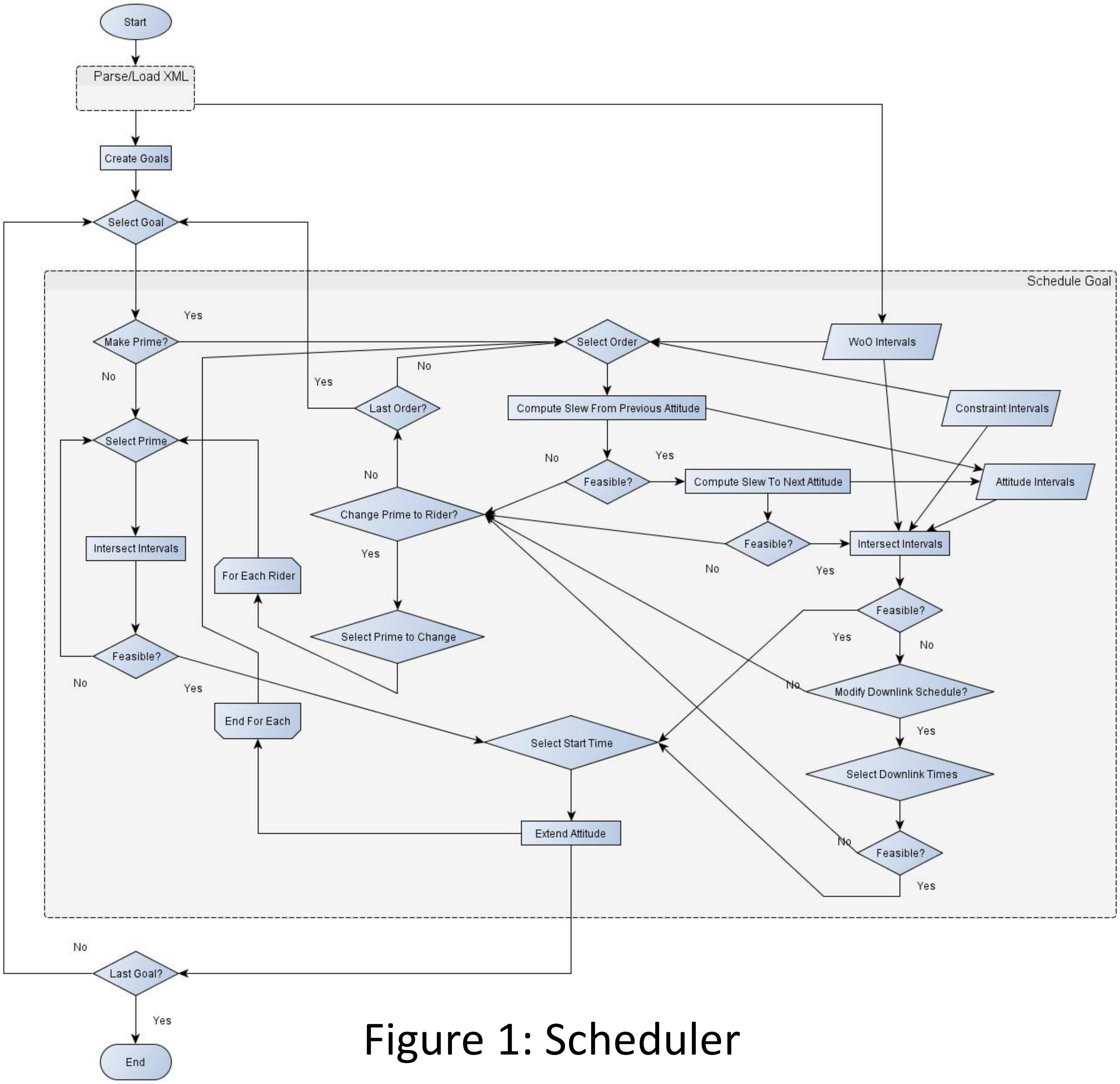
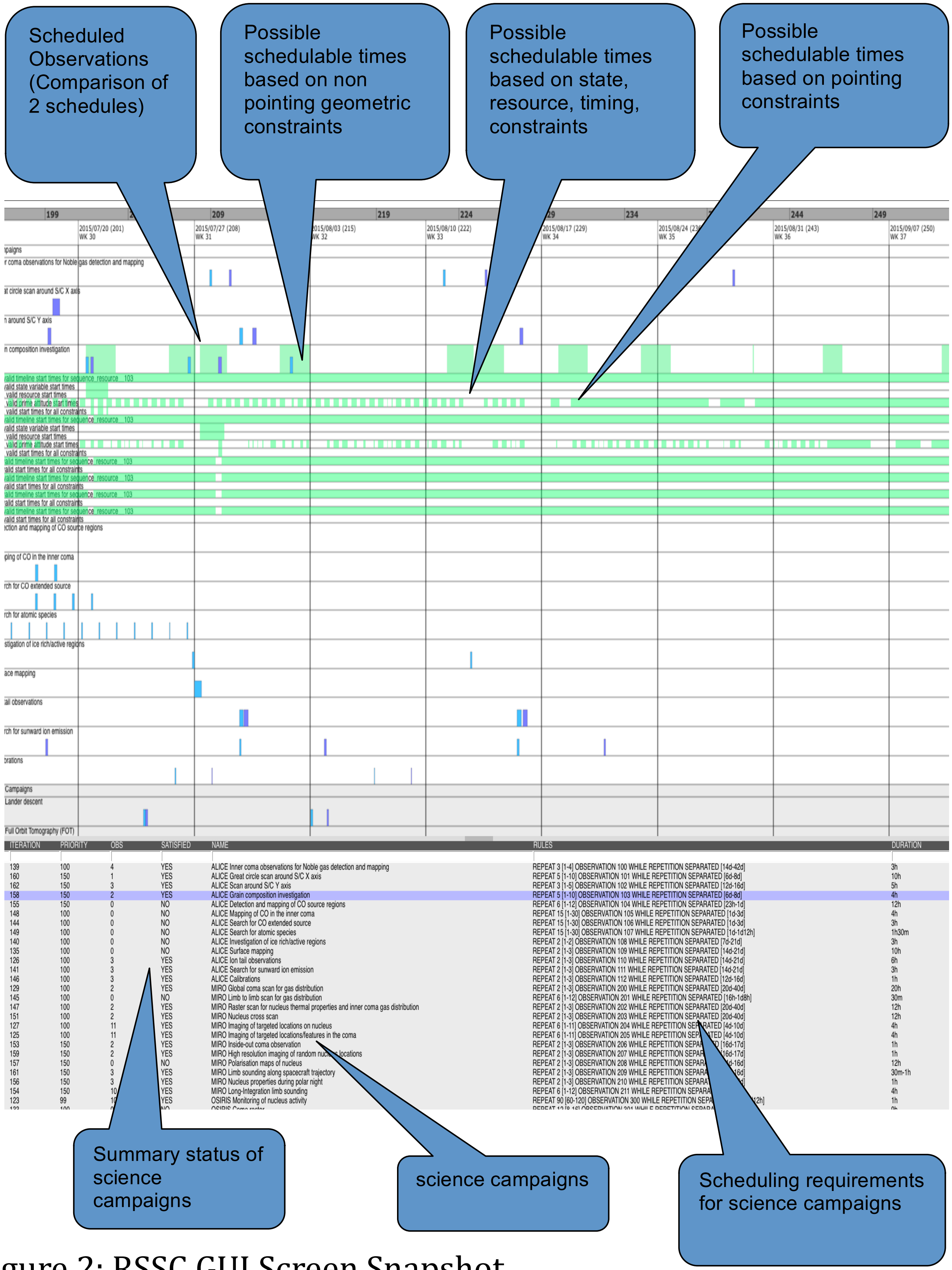


Figure 1: Scheduler



ITERATION	PRIORITY	OBS	SATISFIED	NAME	RULES	DURATION
139	100	4	YES	ALICE Inner coma observations for Noble gas detection and mapping	REPEAT 3 [1-4] OBSERVATION 100 WHILE REPETITION SEPARATED [14d-42d]	3h
160	150	1	YES	ALICE Great circle scan around S/C X axis	REPEAT 5 [1-10] OBSERVATION 101 WHILE REPETITION SEPARATED [6d-8d]	10h
162	150	3	YES	ALICE Scan around S/C Y axis	REPEAT 3 [1-5] OBSERVATION 102 WHILE REPETITION SEPARATED [12d-16d]	5h
158	150	2	YES	ALICE Grain composition investigation	REPEAT 5 [1-10] OBSERVATION 103 WHILE REPETITION SEPARATED [6d-8d]	4h
155	150	0	NO	ALICE Detection and mapping of CO source regions	REPEAT 6 [1-12] OBSERVATION 104 WHILE REPETITION SEPARATED [23h-1d]	12h
148	100	0	NO	ALICE Mapping of CO in the inner coma	REPEAT 15 [1-30] OBSERVATION 105 WHILE REPETITION SEPARATED [1d-3d]	4h
144	100	0	NO	ALICE Search for CO extended source	REPEAT 15 [1-30] OBSERVATION 106 WHILE REPETITION SEPARATED [1d-3d]	3h
149	100	0	NO	ALICE Search for atomic species	REPEAT 15 [1-30] OBSERVATION 107 WHILE REPETITION SEPARATED [1d-1d12h]	1h30m
140	100	0	NO	ALICE Investigation of ice rich/active regions	REPEAT 2 [1-2] OBSERVATION 108 WHILE REPETITION SEPARATED [7d-21d]	3h
135	100	0	NO	ALICE Surface mapping	REPEAT 2 [1-3] OBSERVATION 109 WHILE REPETITION SEPARATED [14d-21d]	10h
126	100	3	YES	ALICE Ion tail observations	REPEAT 2 [1-3] OBSERVATION 110 WHILE REPETITION SEPARATED [14d-21d]	6h
141	100	3	YES	ALICE Search for sunward ion emission	REPEAT 2 [1-3] OBSERVATION 111 WHILE REPETITION SEPARATED [14d-21d]	3h
146	100	3	YES	ALICE Calibrations	REPEAT 2 [1-3] OBSERVATION 112 WHILE REPETITION SEPARATED [12d-16d]	1h
129	100	2	YES	MIRO Global coma scan for gas distribution	REPEAT 2 [1-3] OBSERVATION 200 WHILE REPETITION SEPARATED [20d-40d]	20h
145	100	0	NO	MIRO Limb to limb scan for gas distribution	REPEAT 6 [1-12] OBSERVATION 201 WHILE REPETITION SEPARATED [16h-1d8h]	30m
147	100	2	YES	MIRO Raster scan for nucleus thermal properties and inner coma gas distribution	REPEAT 2 [1-3] OBSERVATION 202 WHILE REPETITION SEPARATED [20d-40d]	12h
151	100	2	YES	MIRO Nucleus cross scan	REPEAT 2 [1-3] OBSERVATION 203 WHILE REPETITION SEPARATED [20d-40d]	12h
127	100	11	YES	MIRO Imaging of targeted locations on nucleus	REPEAT 6 [1-11] OBSERVATION 204 WHILE REPETITION SEPARATED [4d-10d]	4h
125	100	11	YES	MIRO Imaging of targeted locations/features in the coma	REPEAT 6 [1-11] OBSERVATION 205 WHILE REPETITION SEPARATED [4d-10d]	4h
153	150	2	YES	MIRO Inside-out coma observation	REPEAT 2 [1-3] OBSERVATION 206 WHILE REPETITION SEPARATED [16d-17d]	1h
159	150	2	YES	MIRO High resolution imaging of random nucleus locations	REPEAT 2 [1-3] OBSERVATION 207 WHILE REPETITION SEPAR[illegible] [16d-17d]	1h
157	150	0	NO	MIRO Polarisation maps of nucleus	REPEAT 2 [1-3] OBSERVATION 208 WHILE REPETITION SEPARA[illegible]4d-16d]	12h
161	150	3	YES	MIRO Limb sounding along spacecraft trajectory	REPEAT 2 [1-3] OBSERVATION 209 WHILE REPETITION SEPARA[illegible]16d]	30m-1h
156	150	3	YES	MIRO Nucleus properties during polar night	REPEAT 2 [1-3] OBSERVATION 210 WHILE REPETITION SEPARAT[illegible]d]	1h
154	150	10	YES	MIRO Long-Integration limb sounding	REPEAT 6 [1-12] OBSERVATION 211 WHILE REPETITION SEPARA[illegible]	4h
123	99	10	YES	OSIRIS Monitoring of nucleus activity	REPEAT 90 [60-120] OBSERVATION 300 WHILE REPETITION SEPA[illegible]12h]	1h

Figure 2: RSSC GUI Screen Snapshot

Figure 2 shows the web-based RSSC GUI. At the top the observation activities are shows, with each row representing a science campaign. When highlighted, the windows of opportunity are shown for the campaign. When highlighted the constraint windows to schedule individual observations are shown as well. In this mode the user can see which constraints are most restricting the placement of individual observations in the campaign and in the most extreme case preventing the scheduling of the observations. The GUI also shows a schedule comparison view, in which the activities from two schedules are shown on the same campaign timelines side by side or stacked. In this case the blue and purple indicate the two schedules. The blue indicates the science campaign if scheduled in isolation (e.g. not competing against other campaigns). The purple shows the scheduled observations when all of the campaigns are competing. This view allows the user to distinguish between campaigns that are inherently hard to schedule (e.g. due to few geometric opportunities) versus those that are not faring well due to competition with other campaigns (e.g. that might be helped by a boost in priority).

Automated scheduling to support the operational flow has not been emphasized. The operational flow requires that in long term planning an operational plan be developed from the skeleton plan. This operational LTP plan will then be refined further as it evolves into medium term planning (MTP) and short term planning (STP). This involves generating a new plan from an existing plan and a set of updates (changes) to inputs. While this bears some relation to "from scratch" plan generation, the algorithms and methods eventually used may be quite different.

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 1012, November 2012, March 2013) with major integration completing in the Summer of 2013.

The operational system will need to process science plans in early 2014 to prepare for the commencement of the comet escort phase in late Fall 2014. After the spacecraft approaches the comet the lander is deployed and after several weeks of lander operations the primary orbiter escort science phase begins. This primary science phase lasts approximately 9 months.

Related Work

Many scheduling systems have been applied to space mission operations (for a more thorough survey see [Chien et al. 2012]). One unusual aspect of RSSC is the large number of diverse science campaigns represented in RSSC and also the geometric constraints that must be considered across science campaigns.

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].

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.

Conclusions

We have described an automated scheduling system designed to support Rosetta Science Planning as part of the ESAC led Rosetta Science Ground Segment (SGS). We described the two phases of support: skeleton planning and operational planning. 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.

References

J. Bresina, A. Jonsson, P. Morris, K. Rajan, "Activity Planning for the Mars Exploration Rovers," Proceedings International Conference on Automated Planning and Scheduling, 2005, Monterey, CA.

H. M. Calvani, A. F. Berman, W. P. Blair, J.R. Caplingera, M.N. Englanda, B.A. Roberts, R. Hawkins, N. Ferdous, T. Krueger, 2004. The Evolution of the FUSE Spike Long Range Planning System. In *Proceedings of the 4th International Workshop on Planning and Scheduling for Space*, Darmstadt, Germany, 25-31.

A. Cesta, Cortellessa, G., Fratini, S., Oddi, A. and Policella. N. An innovative product for space mission planning: an a posteriori evaluation. In Proceedings of International Conference on Automated Planning and Scheduling, 2007, Providence, RI.

A. Cesta, Cortellessa, G., Denis, M., Donati, A., Fratini, S., Oddi, A., Policella, N., Rabenau, E. and Schulster, J. RAXEM - Supporting Command Uplink in Mars Express. In i-SAIRAS-08, Proceedings of the 9th International Symposium in Artificial Intelligence, Robotics and Automation in Space, Studio City, CA, February, 2008.

S. Chien, G. Rabideau, R. Knight, R. Sherwood, B. Engelhardt, D. Mutz, T. Estlin, B. Smith, F. Fisher, T. Barrett, G. Stebbins, D. Tran, "ASPEN - Automating Space Mission Operations," *SpaceOps 2000*, Toulouse, France.

S. Chien, D. Tran, G. Rabideau, S. Schaffer, D. Mandl, S Frye, "Timeline-based Space Operations Scheduling with External Constraints, " International Conference on Automated Planning and Scheduling, Toronto, Canada, May 2010.

S. Chien, M. Johnston, N. Policella, J. Frank, C. Lenzen, M. Giuliano, A. Kavelaars, "A generalized timeline representation, services, and interface for automating space mission operations, *Space Operations 2012*, Stockholm, Sweden, June 2012.

C. Chouinard, R. Knight, G. Jones, D. Tran, D. Koblick, Automated and Adaptive Mission Planning for Orbital Express, Space Operations 2008, Heidelberg, Germany, 2008.

European Space Agency, http://www.esa.int/Our_Activities/Space_Science/Rosetta

European Space Agency, Rosetta Factsheet, http://esamultimedia.esa.int/docs/rosetta/FactsheetRosetta.pdf

M.P. Geyer, F. Mrowka, C. Lenzen, "TerraSAR-X/TanDEM-X Mission Planning – Handling Satellites in Close Formation", SpaceOps 2010 Book: 'Space Operations: Exploration, Scientific Utilization & Technology Development', Summer 2011.

M. D. Johnston, and G. E. Miller, 1994. Spike: Intelligent Scheduling of Hubble Space Telescope Observations. In Intelligent Scheduling, M. Zweben and M. Fox Eds. Morgan Kaufmann, San Mateo, 391-422.

L. A. Kramer, Generating a Long Range Plan for a New Class of Astronomical Observatories. In *2nd NASA Conference on Planning and Scheduling for Space*.

G. Rabideau, R. Knight, S. Chien, A. Fukunaga, A. Govindjee, "Iterative Repair Planning for Spacecraft Operations in the ASPEN System," *International Symposium on Artificial Intelligence Robotics and Automation in Space*, Noordwijk, The Netherlands, June 1999.

T. Saski, G. Kosugi, R. Hawkins, J.A. Kawai, T. Kusumoto, 2004. Observation scheduling tools for Subaru Telescope. In *Optimizing Scientific Return for Astronomy through Information Technologie (SPIE Vol. 5493)*, P.J. Quinn and A. Bridger Eds. SPIE, 367-372.

G. Simonin, C. Artigues, E. Hebrand, and P. Lopez, "Scheduling Scientific Experiments on the Rosetta/Philae Mission," 18th International Conference on Principles and Practice of Constraint Programming, Quebec City, Canada, October 2012.

B.D. Smith, B.E. Engelhardt, and D.H. Mutz,"The RADARSAT-MAMM Automated Mission Planner," AI Magazine, vol. 23, no. 2, 2002. pp. 25–36.

J.A. Tejo, M. Pereda, I. Veiga, J.P. Chamoun, G. Garcia and T. Beech; "***flexplan***: An Operational Mission Planning & Scheduling COTS Used Internationally", 5th International Workshop on Planning and Scheduling for Space. Baltimore (USA) 2006.