A Constraint-based Data Management Tool for Dawn Science Planning

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Abstract

We describe adaptation of the Automated Scheduling and Planning Environment (ASPEN) planning engine for data management to support Dawn Science Planning for the Ceres encounter.

Dawn is a mission to map two bodies in the main asteroid belt: Vesta and Ceres. The Vesta encounter is complete and the Ceres encounter is currently in planning. One of the challenges of Dawn science planning is to optimize the gathering of images of the target bodies with limited onboard storage space while downlinking acquired science data. An adaptation of the ASPEN planning system has been developed that models the data acquisition of the Dawn spacecraft instruments as well as engineering data. This ASPEN adaptation also models the Dawn data storage buffers, playback modes, and downlink. Finally the adaptation also tracks relevant variables such as filter wheel motions. This tool supports Dawn science planners in assembly of a Dawn data management plan and science observation plan from a set of template data acquisition plan fragments, and reliably verifies that the plan satisfies relevant data throughput, engineering, and other operations constraints. Future plans include the development of more advanced plan repair and/or optimization techniques that offer the potential to enhance Dawn science operations.

1 Introduction

The Dawn mission has already returned unprecedented data from the Vesta encounter in 2011. The Dawn spacecraft [Thomas et al. 2012] is currently en route to study Ceres with a planned encounter in early 2015. In preparation for this encounter, a detailed science observation plan has been carefully designed using the Science Opportunity Analyzer (SOA) [Polanskey et al, 2002, Streiffert and Polanskey 2004] to be robust to many unknowns but most notably the rotational axis, exact rotational period, mass and center of gravity. However, because of the time constraints, and modest operations staff required by the budget of a Discovery class mission, the Dawn Ceres science plan must be completed prior to Ceres arrival.

The Ceres encounter science plan benefits from the experience gleaned from successful operations of the Vesta science plan [Polanskey et al. 2012]. As such the Ceres science plan contains the same basic elements of survey, high altitude mapping orbit (HAMO), and low altitude mapping orbit (LAMO).

However, based on the Vesta experience, many disruptions to the Dawn operations are possible. In order to respond to these disruptions despite a modest operations team, the Dawn mission has been working with the JPL Artificial Intelligence Group in developing a Dawn data management tool to enable a methodical analysis of the data management aspects of Dawn mission operations. This tool encompasses constraint checks and plan validation that previously was performed manually and by constraints implemented in Science Time Ordered Listing (SciTOL).

In the remaining sections of this paper we describe:

1. overall Dawn science planning process,
2. the data management challenge presented by Dawn science operations,
3. the data management planning process using the ASPEN adaptation,
4. future planned work to enable further automation, and
5. relationship of this work to other prior work in tools for science planning as well as data management.

2 The Dawn Spacecraft and Mission To Ceres - Science Planning

The Dawn mission plan is carefully designed to meet the Dawn mission science objectives via a series of investigation and mapping phases at the Ceres body [Polanskey et al. 2014]. In a series of mission phases the Dawn spacecraft will approach Ceres, acquire imagery in a survey phase, then perform a high altitude mapping phase (HAMO), then perform low altitude mapping (LAMO). Within each phase, Dawn will execute a carefully designed mapping campaign that utilizes the relative orientation of the sun, spacecraft, and Ceres to acquire a series of maps of Ceres using all three science instruments (see Table 1 below).

Science Phase	Start Date	End Date	Duration (Days)	Orbital Radius (period)	Duration (Days)
Approach	21 Jan 2015	15 April 2015	100		100
Capture	29 March 2015		n/a		n/a
RC3	15 April 2015	5 May 2015	20		20
Survey	4 June 2015	26 June 2015	22	4900 km (75.0 hrs)	22
HAMO	6 August 2015	15 Oct 2015	56	1950km (19.0 hrs)	56
LAMO	15 Dec 2015	2 March 2016	92	850 km (5.4 hrs)	92
Operations Margin	2 March 2016	24 June 2016	50		50

Table 1: Baseline Ceres Mission Timeline

Dawn will first make a series of three rotation characterizations (RC), in which Ceres is observed for a full rotation period in order to obtain the first global coverage maps. These measurements will enable improved knowledge of the rotational axis and period of Ceres. The first two rotational observations (RC1 and RC2) take place during the approach phase of the Ceres portion of the mission. The third rotational observation (RC3) occurs after approach and before the survey science phase.

After RC3, the baseline plan is that Dawn will perform survey science operations at an orbital altitude of 4900 km. This phase will last for 22 days, and is designed to obtain a global view of Ceres with Dawn's framing camera (FC) [Sierks et al. 2012], and global maps with the Visible and Infrared Spectrometer (VIR) [De Sanctis et al. 2012].

Dawn will then spiral its way down to an altitude of about 1950 kilometers for a 56 day phase known as the high-altitude mapping orbit (HAMO). During this phase, the spacecraft will continue to acquire near-global maps with the VIR and framing camera at higher resolution than in the survey phase. The spacecraft will also image in “stereo” to resolve the surface in 3-D.

Then, after spiraling down for an additional two months, Dawn will begin its closest orbit around Ceres in December, at a distance of about 850 kilometers. The low-altitude mapping orbit will be three months and is specifically designed to acquire data with Dawn's gamma ray and neutron detector (GRaND) [Prettyman et al. 2012] and gravity investigation. GRaND will reveal the signatures of the elements on and near the surface. The gravity experiment will measure the tug of the Ceres dwarf planet, as monitored by changes in the high-precision radio link to NASA's Deep Space Network on Earth.

At this low-altitude mapping orbit, Dawn will begin using a method of pointing control that engineers have dubbed "hybrid" mode because it utilizes a combination of reaction wheels and thrusters to point the spacecraft. Up until this final mission phase, Dawn will have used just the small thruster jets, which use a fuel called hydrazine, to control its orientation and pointing. While it is possible to explore Ceres completely using only these jets, mission managers want to conserve precious fuel. At this lowest orbit, using two of the reaction wheels to help with pointing will provide the biggest hydrazine savings. So Dawn will be spinning up two of the gyroscope-like devices to aid the thrusters.

3 Dawn Data Management Challenges

One challenge of Dawn science operations is managing the data acquired by the main science instruments and returning it to Earth. Because the Dawn spacecraft does not have an articulated High Gain Antenna [Thomas et al. 2011], downlinking data to earth cannot be done concurrently with science operations. Generally speaking the downlinks are scheduled to take place when the Dawn spacecraft is on the unlit side of Ceres so as to not interfere with science observations. However, for certain mission phases a single lit portion of an orbit acquires so much data that a downlink segment must be scheduled on the lit side, interrupting science operations. Current mission operations is futher complicated by the loss of reaction wheels meaning that most turns by the spacecraft are now performed by thrusters. Furthermore, because thruster propellant is the critical mission limiting quantity, turns are now minimized to the greatest extent possible.

The Dawn spacecraft has configurable circular buffers totaling 7.54 Gigabits of which 6 Gigabits is allocated to store science data. Additionally, the FC (8 Gigabits) and VIR (6 Gigabits) also have onboard storage. The data management aspect of the science planning problems is to manage the storage of science data in in the instrument and spacecraft storage buffers so that it can be downlinked intact. The goal of the developed data management tool is to make it as easy as possible for the Dawn operations team to develop an optimized science plan to acquire the best science data to achieve the mission goals while simultaneously developing a data management plan that allows all of the acquired data to be downlinked before being overwritten onboard.

Figure 1 below shows the dataflow onboard the Dawn spacecraft. The three instruments (FC, VIR, GRaND) produce data. FC and VIR data are immediately stored into dedicated instrument buffers. GRaND data must go directly to a downlink virtual recorder (VR), in effect another buffer. FC and VIR data can be transferred from instrument buffers into dedicated downlink virtual recorders (VRs) using specific xB activities but: (1) only one such transfer can be occurring at a time, (2) the data bus must be configured for that source and destination, and (3) the FC and VIR downlink VRs are of limited size. When the Dawn spacecraft is downlinking to Earth using the Deep Space Network, data is read from the downlink VRs freeing them up for additional science data. One key aspect of the downlink problem is configuring the downlink mode which indicates which VRs are downlinked in which order during each DSN downlink. The data management problem is to orchestrate all of these data transfers to get the highest priority data from the instruments to the DSN while not underflowing or overflowing any of the buffers.

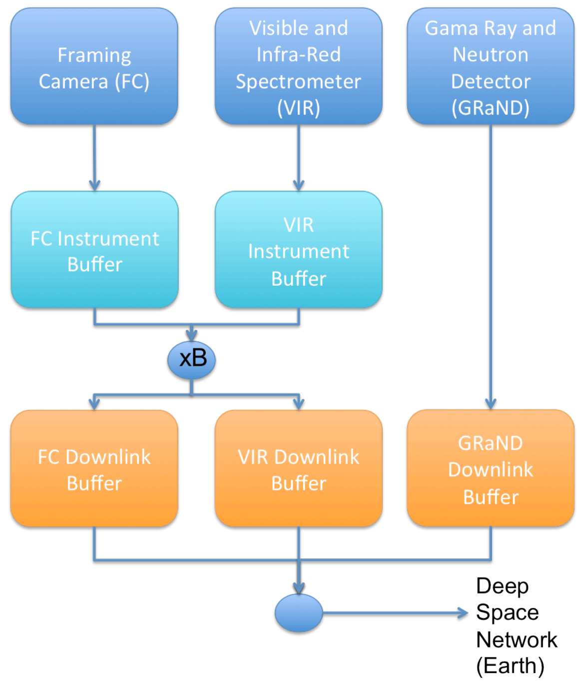

Figure 1: Diagram showing data flow onboard Dawn Spacecraft

4 The ASPEN Dawn Data Management Tool

The Automated Planning and Scheduling Environment (ASPEN) [Chien et al. 2000] is a generic multi-mission tool that has been used to automated planning and scheduling of space mission operations for the several missions including the Modified Antarctic Mapping Mission [Smith et al. 2003] , Earth Observing One Mission [Chien et al 2005, Chien et al. 2010], The Orbital Express Mission [Chouinard et al. 2008, Knight et al. 2014], and Rosetta Orbiter Science Operations [Chien et al. 2013].

The Dawn mission has already planned and executed a successful Vesta encounter. In the planning and execution of the Vesta encounter they used the SciTOL (Science Time Ordered Listing) system to track and model spacecraft commanding and data flow for science planning purposes [Polanskey et al. 2010]. For the Ceres encounter, the Dawn mission is augmenting the SciTOL system with the ASPEN adaptation, which is the focus of this paper. The rationale behind this approach is severalfold:

1. to increase the robustness of operations by redundant constraint modeling and checks in both SciTol and ASPEN and

2. to enable the potential for greater automation via ASPEN automated planning,

3. potentially enable operations support by personnel with less detailed SciTOL knowledge, and

4. increase the fidelity of the buffer model. Enabling increased mission return by reducing margins.

Specifically, at Vesta, mission policy was to carry a 20% data volume margin. Due to improved fidelity modeling, at Ceres ASPEN runs are performed carrying a 10% data volume margin, enabling return of more science data. Additionally, due to the failure of reaction wheels since the Vesta encounter, the number of turns to perform downlinks by Dawn at Ceres is to be minimized (since each turn uses valuable hydrazine). This has placed a premium on efficient data management. Again, more detailed data buffer modeling by ASPEN enables more accurate tracking of data volume to more efficiently manage downlinks.

In the current Ceres encounter planning process thus far, the Dawn planning team has used the following process:

1. Develop the observation patterns in the Science Opportunity Analyzer [Polanskey et al. 2002, Seiffert and Polanskey 2004]

2. Develop an initial plan in SciTOL [Polanskey et al. 2012]

3. Develop ASPEN input files to match the SciTol plan

4. Run ASPEN for detailed constraint checking, manually iterate to resolve any problems found

5. When satisfactory ASPEN plan completed, export this back to SciTOL.

In the operational flow, both SciTOL and ASPEN are used as constraint checking tools in the science plan development. The ASPEN model models many constraints in the data flow, instrument operations, and spacecraft operations in order to correctly model the data management of the Dawn Mission. Specific ASPEN plan fragments are represented as plan templates that represent types of Dawn operational orbits (e.g. with specific imaging, data transfer, and downlink patterns). When a plan is assembled in ASPEN, it is constructed by referring to a potentially large set of orbit templates, each of which is applied with a start epoch (such as the s/c crossing from night to day terminator) and time offset (which may be zero). A set of these templates might then represent a plan for a cycle. The ASPEN planning process for that cycle would then be to construct the plan by specifying many of these template instantiations, loading them into ASPEN, and then noting conflicts. The next step would then be to manually repair the conflicts by adjusting the templates, most often by adjusting playback and downlink timing.

Specifically relevant to data management, the ASPEN model tracks the three instruments operations and data generation at the instrument, storage in the instrument buffer(s), transfers of data from the instrument buffers into the spacecraft (VR) buffers, and subsequent downlink modes.

The ASPEN model for Dawn covers a wide range of instrument and spacecraft activities relevant to Dawn data management and includes 192 activity types, 58 resources, and 62 states. These include power, data volumes, data rates, and operational modes for the instruments as well as buffers (instrument and spacecraft) relevant to data management and downlink. Several instruments also have cover states. Additionally, ASPEN models the filter wheel state in order to calculate filter wheel motions that are tracked as a consumable. The overall mode of the spacecraft propulsion / pointing (e.g. thrusting, turning, etc.) is modeled as well as if the spacecraft is in occultation or not.

A typical planning horizon for analysis in a single run example is 43 days of Low Altitude Mapping Orbit (LAMO) for Ceres (e.g., a subset of the 90+ day LAMO in the current baseline mission plan). An early run of this mission phase had 50 unique template files that expanded into 68 plan fragment (ini) files. This planning run included 527 VIR related activities, 640 FC related activities, and 769 playback related activities. In all a total of 14825 total mission activities occur in this ASPEN run.

To date, ASPEN has been used in combination with SciTOL to support Dawn Ceres encounter science plan development since Summer 2013 to present (late Spring 2014).

Figure 2 below shows a typical plan fragment modeled in the ASPEN Dawn adaptation. At the top exogenous events such as DSN passes are displayed. At the middle the instrument downlink buffers (VR's) are displayed. Below the VR's the spacecraft transfer/xB playback mode is shown, indicating how the data is being transferred at various times from the instrument buffer to downlink buffer, to the DSN as the specific plan progresses. The bottom area shows the planned spacecraft state as the plan executes.

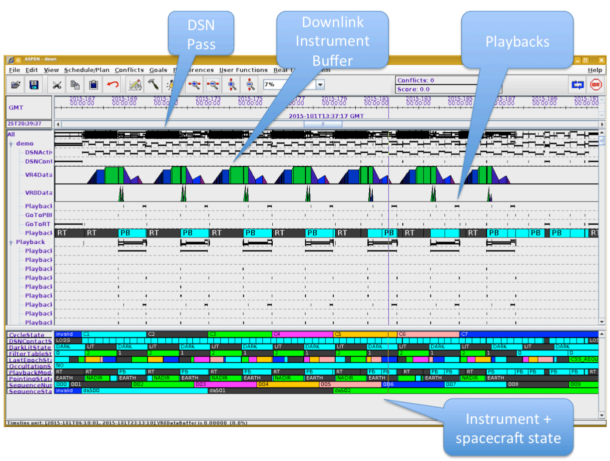

Figure 2: ASPEN Graphical User Interface Displaying Dawn Data Management Plan.

4.1 Future plans to enhance the ASPEN Data Management Tool

The Dawn team and ASPEN team have identified a number of areas of future work to enhance the Dawn ASPEN tool. We outline several of these areas below.

1. Automatic methods of initially adapting templates: currently when templates are assembled into a coherent plan, adjustment of the templates must be performed manually. This can be tedious and can result in heterogeneous plans due to use of alternative methods to make a plan consistent at different planning times. One area of automation would be to have ASPEN invoked by the human planner to apply prescribed methods to make the ASPEN plan consistent. For example, the first preference is to reduce margins to make the plan consistent.

2. Automated replanning to DSN track updates: for future work, we intend to integrate an ability to ingest a schedule from the Deep Space Network (DSN) and incorporate it into Dawn operations plan. Dawn operations are planned out far in advance using an assumed schedule of DSN support, which may change as they approach the present. Furthermore there are short gaps of connectivity for setting up link as antennas are switched, which early planning will incorporate margins for, but not directly schedule the necessary pause commands in VR playback to avoid loss of data. We will enhance the ASPEN model to incorporate DSN track activities to represent the ingested DSN schedule, including adjustments for one-way-light-time and track-setup and track-teardown margins, where each activity will reserve on a depletable timeline counting the number of "tracks." A requirement will be added to the existing playback timelines/activities to require at least one track while the "playback" state is active. This will provide a conflict to guide the operations planner in adding necessary pause/resume activities (effecting the "playback" state). Further work will add a capability to automate the insertion, or suggesting insertion of these activities.

4.2 Related Work to the ASPEN Dawn Data Management Tool

Automated planning and scheduling has been used on a wide range of mission (see [Chien et al. 2012] for a survey). However, most of these applications address the overall mission planning and scheduling problem whereas the Dawn-ASPEN tool focuses on the data management aspect of the planning problem.

One drawback of the current Dawn planning architecture is that the data management and geometric observation problem are solved by separate systems: Science Opportunity Analyzer (SOA) for the geometric observation planning and SciTOL and ASPEN for the data management problem. In an ideal solution these problems would be solved simultaneously or at least in a more closely coupled system.

One related system is the MEXAR2 [Cesta et al. 2007, 2008] resulted in a 50% reduction in downlink data management planning for Mars Express and increased robustness due to ability to optimize and produce multi-day/week lookahead plans. MEXAR2 uses a downlink lookahead scheduling strategy to ensure no buffer under/over runs by planning which data goes down at each downlink pass. The focus of MEXAR2 is therefore which data is downliked at each downlink opportunity. In contrast, the Dawn-ASPEN tool is more focused on tactical playback, e.g. managing the data flow during a playback between the instrument buffer and corresponding downlink buffer with lesser emphasis on across multiple playback optimization.

5 Conclusions

We have presented the use of the ASPEN planning framework as applied to constraint checking for data management planning for the Dawn mission. In this work, the ASPEN system has been adapted to represent a significant number of Dawn data volume, state, timing, and instrument operations constraints to support development of large Dawn data management plans. In this approach, ASPEN works with existing Dawn tools such as the Science Opportunity Analyzer (SOA) and Science Time Ordered Listing (SciTOL) to assist in the development of the detailed observation plan. In this ASPEN adaptation, ASPEN models the dataflow, data storage, and spacecraft activities relevant to the data flow and assists the science planners in developing the overall data management aspect of the science plan. While currently ASPEN's primary role is as a constraint checker, future plans are to enable ASPEN to propose plans for data transfer either as an initial data transfer plan or in response to changing Deep Space Network downlink availability or spacecraft events.

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References

A. Cesta, Cortellessa, G., Fratini, S., Oddi, A. and N. Policella. 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, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, D. Mandl, S. Frye, B. Trout, S. Shulman, D. Boyer, "Using Autonomy Flight Software to Improve Science Return on Earth Observing One," Journal of Aerospace Computing, Information, and Communication, Apr. 2005, pp. 196–216.

S. Chien, D. Tran, G. Rabideau, S. Schaffer, D. Mandl, S. Frye, "Timeline based Space Operations Scheduling with External Constraints, Proceedings of the 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 Symposium, Stockholm, Sweden. June 2012.

S. Chien, G. Rabideau, D. Tran, F. Nespoli, D. Frew, H. Metselaar, M. Kueppers, M. Fernandez, L. O'Rourke, Scheduling Science Campaigns for the Rosetta Mission: A Preliminary Report," International Workshop on Planning and Scheduling for Space (IWPSS 2013). Moffett Field, CA. March 2013.

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

M. C. De Sanctis, A. Coradini, E. Ammannito, G. Filacchione, M. T. Capria, S. Fonte, G. Magni et al. "The VIR spectrometer." In *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*, pp. 329-369. Springer New York, 2012.

R. Knight, C. Chouinard, G. Jones, and D. Tran, Automated Mission Planning for Orbital Express, AI Magazine, to appear, 2014.

C. A. Polanskey, B. Streiffert, T. O'Reily, J. Colwell, Advances in science planning, Space Operations 2002, October 2002, Houston, TX.

C. A. Polanskey, S. P. Joy, and C. A. Raymond, "Dawn Science Planning, Operations, and Archiving," In *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*, pp. 175-249. Springer New York, 2012.

C. A. Polanskey, S. P. Joy, C. A. Raymond, M. D. Rayman, Architecting the Dawn Ceres Science Plan, Space Operations, Pasadena, CA, May 2014.

T. H. Prettyman, W. C. Feldman, H. Y. McSween Jr, R. D. Dingler, D. C. Enemark, D. E. Patrick, S. A. Storms et al. "Dawn's gamma ray and neutron detector." In The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres, pp. 371-459. Springer New York, 2012.

H. Sierks, H. U. Keller, R. Jaumann, H. Michalik, T. Behnke, F. Bubenhagen, I. Büttner et al. "The Dawn framing camera." Space science reviews 163, no. 1-4 (2011): 263-327.

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.

B. Streiffert and C. Polanskey, "Science Opportunity Analyzer: not just another pretty face," Space Operations Symposium, May 2004, Montreal, Canada.

V. C. Thomas, J. M. Makowski, G. M. Brown, J. F. McCarthy, D. Bruno, J. C. Cardoso, W. M. Chiville et al. "The dawn spacecraft." In *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*, pp. 175-249. Springer New York, 2012.