Multi-Objective Scheduling for Space Science Missions

Mark D. Johnston* and Mark Giuliano**

*Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena CA USA 91109
mark.d.johnston @jpl.nasa.gov

**Space Telescope Science Institute
3700 San Martin Drive, Baltimore MD 21219
giuliano @stsci.edu

Abstract

We have developed an architecture called MUSE (Multi-User Scheduling Environment) to enable the integration of multi-objective evolutionary algorithms with existing domain planning and scheduling tools. Our approach is intended to make it possible to re-use existing software, while obtaining the advantages of multi-objective optimization algorithms. This approach enables multiple participants to actively engage in the optimization process, each representing one or more objectives in the optimization problem. As initial applications, we apply our approach to scheduling the James Webb Space Telescope, where three objectives are modeled: minimizing wasted time, minimizing the number of observations that miss their last planning opportunity in a year, and minimizing the (vector) build up of angular momentum that would necessitate the use of mission critical propellant to dump the momentum. As a second application area, we model aspects of the Cassini science planning process, including the trade-off between collecting data (subject to onboard recorder capacity) and transmitting saved data to Earth. A third mission application is that of scheduling the Cluster 4-spacecraft constellation plasma experiment. In this paper we describe our overall architecture and our adaptations for these different application domains. We also describe our plans for applying this approach to other science mission planning and scheduling problems in the future.

1 Introduction

Multi-objective scheduling is an approach to optimized scheduling that offers a number of advantages over the more conventional single-objective approach[1, 2]. By keeping objectives separate instead of combined, more information is explicitly available to the end user or to the scheduling software system for comprehending and deciding on trade-offs among competing objectives. Multi-objective algorithms produce a set of solutions, called a *Pareto surface* (aka trade-off space), where no solution is strictly dominated by another solution for all objectives. Particularly when objectives cannot be cast to commensurate scales, visibility into the Pareto trade-off space can be extremely valuable for the decision maker. Algorithms for solving multi-objective problems have been developed that are effective in building up populations of candidate schedules that approximate the Pareto frontier with uniform sampling. However, adapting a multi-objective scheduling approach to an operational setting is faced with at least two significant additional challenges:

- the often high dimensionality of the objective space can be difficult to convey to users using conventional graphical user interfaces: this makes it difficult to see overall patterns and trade-offs, or to see the effects of limiting objective or constraint value ranges
- the nature of many multi-objective scheduling problems requires multiple users to be heavily involved, each such user contributing one or more objectives that reflect their interest in the outcome of the scheduling process: thus there is a tightly integrated multi-user aspect that must be considered

We have applied a multi-objective scheduling approach to several space science missions that amply illustrate these challenges: the James Webb Space Telescope (JWST), the Cassini mission at Saturn, and the Cluster 4-spacecraft Wideband Data (WBD) plasma experiment. In this paper we describe the nature of some of the scheduling and user interface challenges that these kinds of missions present, and the techniques we are investigating to overcome them.

2 Approach

We have developed an architecture called MUSE (Multi-User Scheduling Environment) to integrate pre-existing scheduling components (e.g. scheduling engines and user interfaces) into a multi-objective multi-user scheduling framework. The MUSE architecture integrates both generic and application-specific components. Among the generic components is a means for visualizing objective value spaces for schedule populations, for registering objective limits and acceptable ranges, and for collaborative convergence on mutually acceptable schedules for multiple users. Our approach to visualization includes a variety of techniques to meet the challenges noted above of higher-dimensional objective spaces, including 2- and 3-D projections of the Pareto frontier, histograms and other depictions of values in different dimensions, and attribute exploration techniques that have been successfully used in a number of data visualization applications. We have adapted elements common to mixed-initiative user interfaces that can be applied to our domain. The overall architecture and approach to visualization is described in Section 3, and its applica-

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tion to three representative space science missions in Section 4. We summarize our conclusions in Section 5.

3 Architecture

The MUSE architecture is illustrated in Figure 1. Several drivers have led to design decisions as they relate to the architecture:

- MUSE is intended to integrate with existing tools as easily as possible, to leverage existing work in many domains
- The collaborative elements of MUSE require persistent storage of various types of schedule data, hence a server-centric architecture
- Both *online* and *offline* collaboration need to be supported, in consideration of users working across multiple time zones — thus live interaction is available but not required

We distinguish server components (Figure 1 lower half) from those resident on the user's workstation. We also distinguish generic components (left) from those that are generally very domain specific (right). The architecture is designed so that domain specific components can be run as separate processes or can be compiled into the same image as the generic code.

We have adopted the familiar threaded email or newsgroup interaction model as a metaphor for how MUSE interacts with individual participants. Such interaction can be either on- or offline, in that one can tell upon returning to the interface what has changed since one was last present. This is important in settings where participants may use the system in an infrequent episodic manner.

On the server side, the Multi-Participant Coordinator acts as a central "clearing house" for schedule data, participant's selections, and scheduling runs. It provides a REST-based web application interface that communicates with the individual participants, providing up to date schedules, schedule status, and other participants selections of objective value ranges. The Multi-Objective Scheduler is an implementation of an evolutionary algorithm[1, 2] to evolve a population of candidate schedules towards the Pareto-optimal surface. While various algorithms could be employed here, we are presently using a variant called Generalized Differential Evolution[3, 4]. More details about this algorithm and how it performs on some relevant domains may be found in [5]. The Application Map provides a transformation between decision variable values and domain-specific scheduling decisions as represented and evaluated in the Domain Scheduling Engine components. The Multi-Objective Scheduler supports parallel evaluations of schedules, which can frequently help speed the generation of a Pareto surface for participants.

The Domain Scheduling Engine is the application-specific scheduling software that MUSE uses to evaluate candidate schedules. This evaluation utilizes the decision variable values, and can potentially perform internal conflict resolution or optimization steps on its own before returning a set of objective function values to the Multi-Objective Scheduler. These values are used by the evolutionary algorithm to evolve the candidate population towards a well-sampled Pareto surface.

Just as Domain Scheduling Engines can be highly application specific, so are Domain Scheduling GUIs. These GUIs often already exist in many domains and are able to display and manipulate aspects of the scheduling problem that are not common from one domain to another. MUSE is intended to integrate with such GUIs, e.g. to invoke the GUI on one user-selected schedule for detailed examination and assessment.

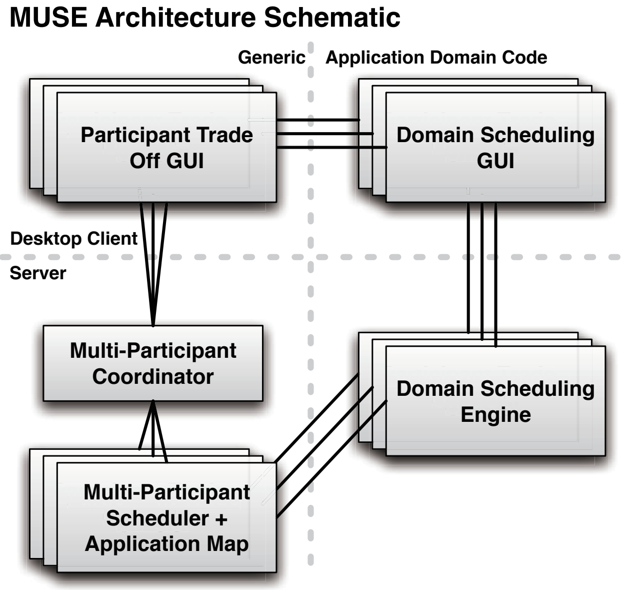


Figure 1. Architectural overview of the Multi-User Scheduling Environment (MUSE).

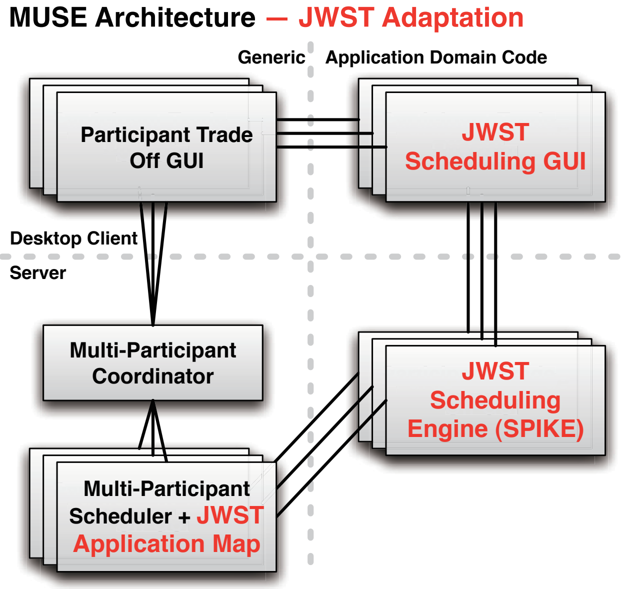
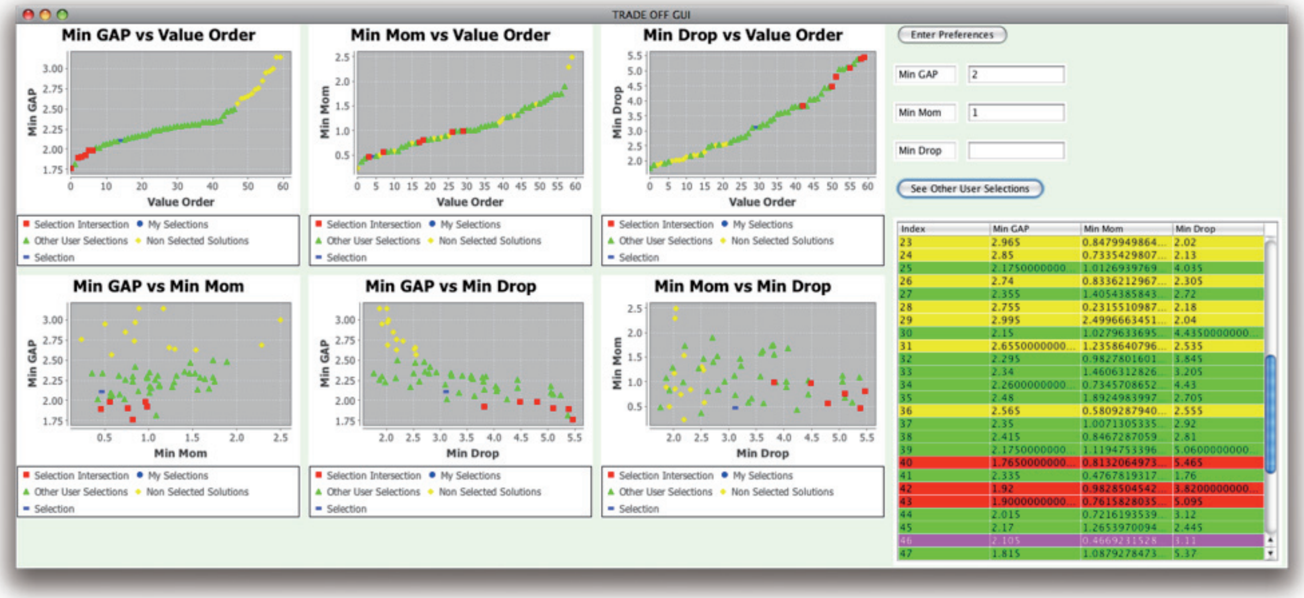


Figure 2. Adaptation of MUSE for a specific domain, here illustrated by James Webb Space Telescope (JWST).



Min GAP 2

Min Mom 1

Min Drop

Index	Min GAP	Min Mom	Min Drop
23	2.965	0.8479949864...	2.02
24	2.85	0.7335429807...	2.13
25	2.1750000000...	1.0126939769...	4.035
26	2.74	0.8336212967...	2.305
27	2.355	1.4054385843...	2.72
28	2.755	0.2315510987...	2.18
29	2.995	2.4996663451...	2.04
30	2.15	1.0279633695...	4.4350000000...
31	2.6550000000...	1.2358640796...	2.535
32	2.295	0.9827801601...	3.845
33	2.34	1.4606312826...	3.205
34	2.2600000000...	0.7345708652...	4.43
35	2.48	1.8924983997...	2.705
36	2.565	0.5809287940...	2.555
37	2.35	1.0071305335...	2.92
38	2.415	0.8467287059...	2.81
39	2.1750000000...	1.1194753396...	5.0600000000...
40	1.7650000000...	0.8132064973...	5.465
41	2.335	0.4767819317...	1.76
42	1.92	0.9828504542...	3.8200000000...
43	1.9000000000...	0.7615828035...	5.095
44	2.015	0.7216193539...	3.12
45	2.17	1.2653970094...	2.445
46	2.105	0.4669231528	3.11
47	1.815	1.0879278473...	5.37

Figure 3. A view of the prototype Participant Trade-Off GUI for a 3-objective domain (JWST).

A key function of the Participant Trade-Off GUI is visualization of the objective space of the problem, in order to comprehend trade-offs and develop a solution acceptable to all participants. For 2- and 3-dimensional objective spaces, there exist commonly used techniques for visualization that can convey the selection possibilities of the candidate schedule population. However, as the dimensionality of the objective space increases, this becomes more and more challenging[6, 7]. We are investigating a number of techniques in this context for displaying higher dimension objective spaces, including:

- parallel coordinate plots
- “brushed” histograms or scatter plots that indicate correlations among attributes
- display of neighbors of selected points when projected to 1- or 2-D displays
- use of multi-touch displays for rapid and intuitive manipulations of selections and views

We expect that user preferences will play a crucial role in this area, and that a wide range of visualization options should be provided to accommodate the wide range of user preferences. We anticipate defining a “plug-in” mechanism so that it is easy to add additional visualization strategies as they become available.

A sample screen from a prototype Participant Trade-Off GUI is shown in Figure 3, in this case for the 3-objective JWST domain (described below). With the Participant Trade-Off GUI users can view a set of candidate schedules, select limit ranges on objective values, and see what other users have selected. They can examine trade-off opportunities objective by objective and update their selections, and see the overall intersection of acceptable ranges from all participants. The ultimate goal is the convergence of all participants to a single selected baseline schedule; should this not occur, MUSE does not preclude any specific process from arbitrating differences and making a final selection.

4 Applications

We have applied the architecture described above to three very different space mission applications, which we describe in the following subsections.

4.1 James Webb Space Telescope

The James Webb Space Telescope (JWST, Figure 4) will be the premier astronomical facility of the next decade, replacing two of the current Great Observatories, Hubble Space Telescope (HST) and Spitzer Space Telescope (SST) as a uniquely capable space-based observatory with highly

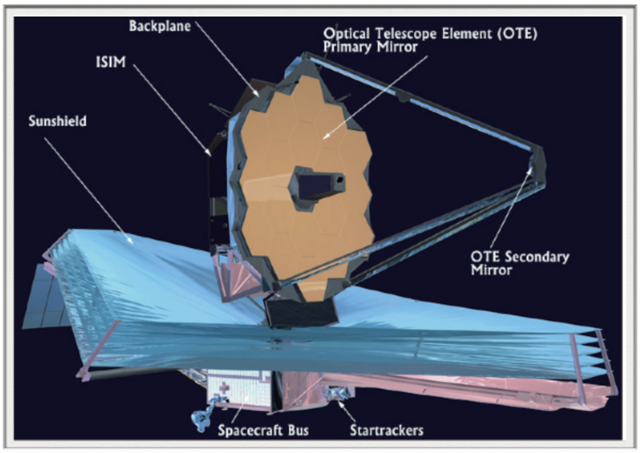


Figure 4. Illustration of James Webb Space Telescope showing the segmented primary mirror and the very large sunshade.

ambitious scientific objectives. Scheduled for launch in 2014, JWST will have a 6.5m primary mirror diameter (compared to 0.85m for SST, and 2.4m for HST), and will primarily observe in the infrared (like SST, and in contrast to HST's primarily optical and UV sensitivity).

Scheduling a mission such as JWST requires the balancing of many factors[8]. Clearly, such an expensive and unique facility must be utilized as efficiently as possible, and minimizing any wasted time is a primary objective. At the same time, the lifetime of the observatory is limited by consumables such as propellant for reducing momentum build-up in the spacecraft's reaction wheels. Thus, optimization of the JWST schedule is determined by multiple simultaneous objectives, for which there is no well-defined trade-off mechanism that would permit definition of a single combined objective. Multi-objective techniques that keep the objectives separate permit explicit visibility and management of the multiple trade-offs that are necessary to generate a balanced overall schedule for JWST.

For JWST, two of the primary objectives are minimizing schedule gaps, and minimizing the number of late observations, i.e. that miss their last scheduling opportunity. The more unusual objective is that of reducing angular momentum build-up in the spacecraft reaction wheels, caused by a complex interaction of pointing direction, roll angle, and solar radiation pressure on the tennis court-sized sunshade. Angular momentum build-up must be compensated by firing spacecraft thrusters, which consumes scarce propellant and thus is potentially a limiting factor on mission lifetime. The angular momentum resource constraint has several important features: it is a 3-dimensional vector additive quantity that applies both as a hard constraint and as a preference. The contribution to angular momentum build-up of any particular observation is a function of when it is scheduled and of the roll angle at which it is scheduled.

The adaptation of the generic MUSE architecture to JWST is illustrated in Figure 2. As the JWST domain scheduler we used Spike[9], implemented in Lisp. The MUSE infrastructure is implemented in Java with the JavaFX scripting language providing user interface functionality. The two systems are integrated via a client-server socket interface that can be readily supported on both sides of the interface. This allows for the exchange of decision variable values from the multi-objective optimizer, and the receipt of objective values in return. Results from the application of the multi-objective optimizer in this manner have been reported elsewhere[10, 11].

Figure 4 illustrates the Participant Trade-Off GUI operating in the JWST context, showing a display of the three objectives described above. This particular visualization shows a rank ordered plot of each objective value in the top three graphs, and the three 2-D projections in the bottom three. All of the points are cross-linked, in that selection of any point in any of the graphs, or any row of the table, will highlight the selected point on all of the other graphical and tabular views. The selection of an objective value range (via the entry boxes, upper right) highlights the selected subpopulation. In addition, the user can view other participant's selections, and the overall intersection of all objective ranges. Finally, the user can publish their own selections to be available to other participants.

4.2 Cassini

As a second application area, we are modeling several aspects of the Cassini science planning process[12, 13], including the trade-off between collecting data (subject to onboard recorder capacity) and transmitting saved data to Earth, which requires a maneuver to point the high-gain antenna to Earth. The choice of downlink timing and ground-based antenna size (70m vs. 34m) has a major impact on how much data can be collected and transmitted, and propagates back to the different science teams in terms of which instruments are in use and in which modes. Thus, there is a natural framing as a multi-objective optimization problem.

The Cassini spacecraft (Figure 5) was launched in 1997 and since 2004 has been in orbit around Saturn. Cassini is a 3-axis stabilized spacecraft with 12 diverse science investigations, including 6 for optical and microwave remote sensing, and 6 for fields/particles/waves. The mission has been a spectacular success, with 260 scientists from 17 countries participating in the scientific data analysis and follow-up. The spacecraft communicates to Earth primarily through a high-gain antenna that must be pointed at Earth, sending back of order one Gigabyte of science data per day.

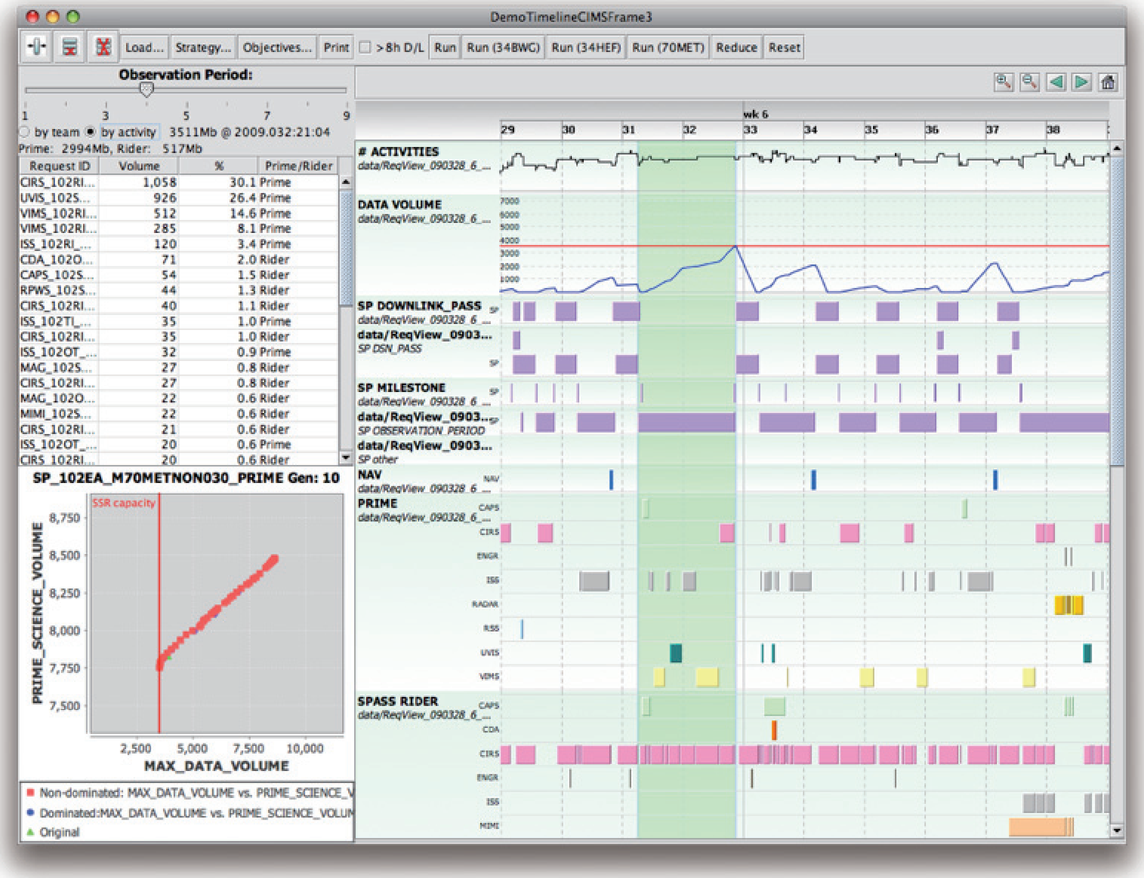
Figure 5. The Cassini/Huygens spacecraft. The white-suited figure at lower left shows the scale

During downlink periods, most of the pointed instruments cannot be used. Thus the timing of science observations and of the downlinks must be scheduled very carefully with respect to interesting observing opportunities, in order to collect and return as much science data as possible while not overfilling the onboard recorder. One of the Cassini objectives that we have modeled is based on this onboard recorder capacity limit. While this could be modeled as a constraint that must not be violated, we have chosen instead to define an objective to minimize the maximum data volume recorded, accounting both for the collection of data by the science instruments, and the dumping of data to the ground. Thus the schedule can be in an infeasible state while it is being worked on, which is useful since the degree of violation of the constraint is very visible to the user. As a second objective, we have chosen to maximize the total science data volume collected. The initial set of activities to be scheduled is defined by the science teams working with the science planners. The strategies that can be employed for improving the schedule with respect to data volume include:

- Extending or reducing the planned downlink opportunity windows, with a corresponding decrease or increase in the time spent collecting science data.
- Changing a 70m contact to a 34m one or vice versa: a 70m contact can download nearly three times as much data, but can be more difficult to obtain.
- Performing an across-the-board reduction in data collected, achievable in an instrument-dependent way (e.g. possibly by switching to a less data intensive operational mode).

These strategies are encoded in the decision variables passed to the scheduling engine.

Figure 6 shows a domain-specific GUI illustrating this problem for a 10-day schedule period, illustrating a 2-D Pareto surface generated by the multi-objective evolutionary algorithm. As the user selects points on the Pareto frontier (lower left), the Gantt view (right) changes to show the detailed implementation of that schedule. The constraining data recorder volume is shown at the top of the Gantt view, where the red horizontal line shows the data volume limit. The tabular view on the right shows all of the contributors to the recorded data volume at the start of each downlink window. This table includes both primary and secondary ("rider") activities, and can be sorted by data volume, percentage of total data on recorder, science team, or activity identifier.



○ by team ● by activity 3511Mb @ 2009.032:21:04
Prime: 2994Mb, Rider: 517Mb

Request ID	Volume	%	Prime/Rider
CIRS_102RI...	1,058	30.1	Prime
UVIS_102S...	926	26.4	Prime
VIMS_102RI...	512	14.6	Prime
VIMS_102RI...	285	8.1	Prime
ISS_102RI_...	120	3.4	Prime
CDA_102O...	71	2.0	Rider
CAPS_102S...	54	1.5	Rider
RPWS_102S...	44	1.3	Rider
CIRS_102RI...	40	1.1	Rider
ISS_102TI_...	35	1.0	Prime
CIRS_102RI...	35	1.0	Rider
ISS_102OT_...	32	0.9	Prime
MAG_102S...	27	0.8	Rider
CIRS_102RI...	27	0.8	Rider
MAG_102O...	22	0.6	Rider
MIMI_102S...	22	0.6	Rider
CIRS_102RI...	21	0.6	Rider
ISS_102OT_...	20	0.6	Prime
CIRS_102RI...	20	0.6	Rider

Figure 6. A view of a Cassini schedule illustrating the Pareto trade-off in the lower left and a Gantt chart view of the various scheduled activities. Onboard data storage is limited to the value indicated by the red line in the Gantt view (second chart from top).

4.3 Cluster WBD Scheduling

Cluster II[14] is an ESA mission consisting of four identical spacecraft in a tetrahedral formation (Figure 7). Cluster is investigating the Earth's magnetic environment and its interaction with the solar wind in three dimensions. One of the instruments on Cluster is the Wideband Data (WBD) plasma wave experiment[15]. The WBD instrument on each of the four Cluster spacecraft operate by providing high-resolution measurements of the electric and magnetic fields in a range of frequency bands. There is no onboard storage for WBD and real-time data from the instrument is sent directly to earth to NASA's Deep Space Network (DSN) antennas. Several factors make scheduling WBD a challenging problem:

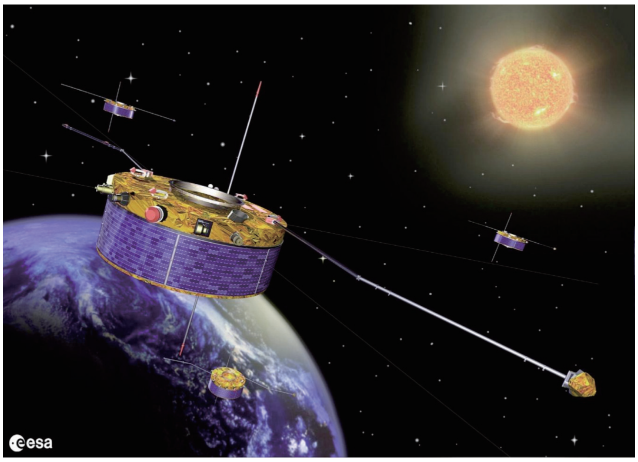
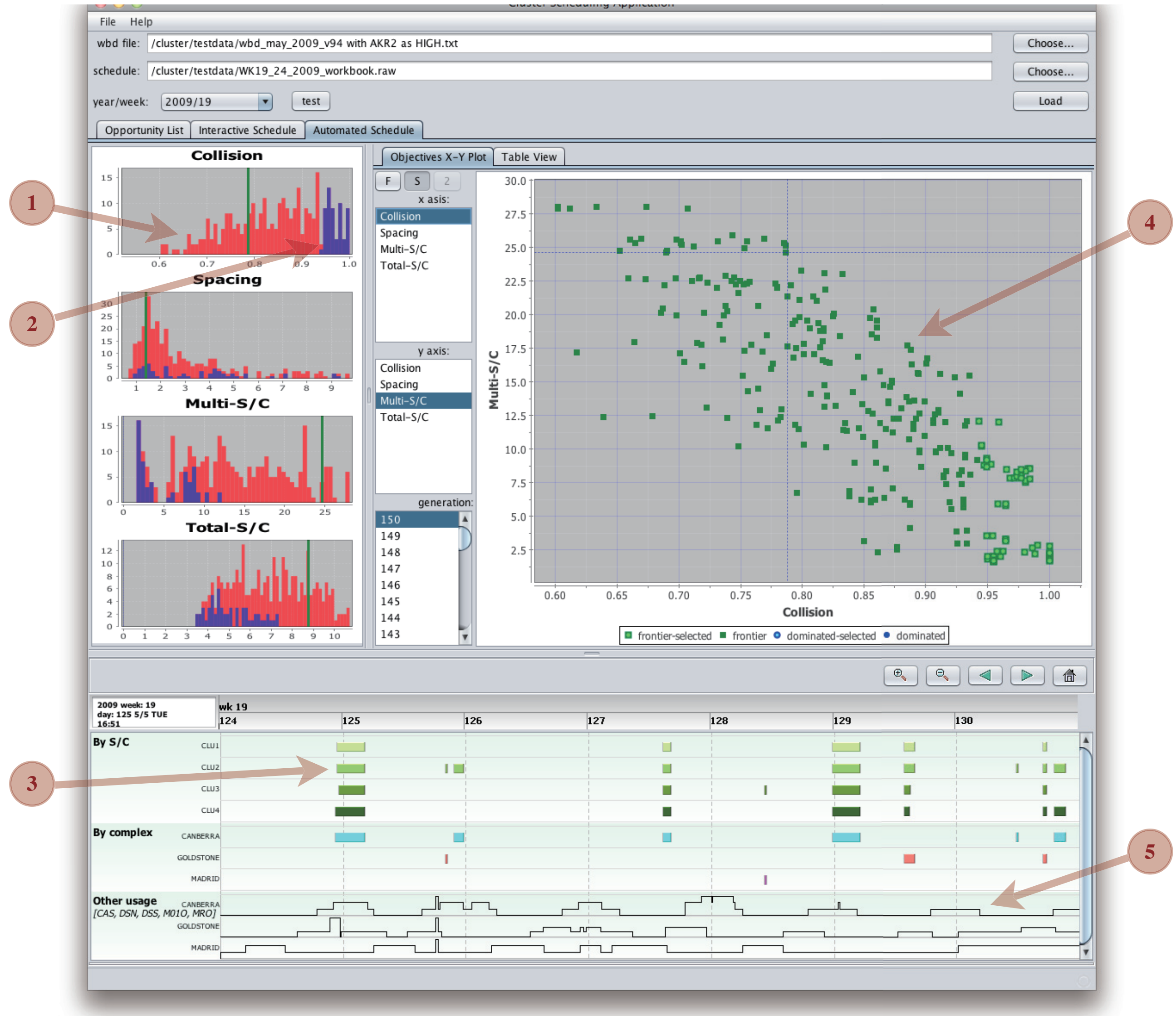


Figure 7. Illustration of the ESA Cluster II four-spacecraft constellation



wbd file: /cluster/testdata/wbd_may_2009_v94 with AKR2 as HIGH.txt

schedule: /cluster/testdata/WK19_24_2009_workbook.raw

year/week: 2009/19

2009 week: 19
day: 125 5/5 TUE
16:51

Figure 8. MUSE multi-objective optimization applied to a one-week Cluster WBD schedule. Visualization of the 4-D Pareto frontier is assisted by 2-D projections and "brushed" histograms (left). Numbered features are described in the text.

- To take an observation requires that the Cluster spacecraft be in a scientifically interesting region of the magnetosphere at the same time it is in the field of view of a DSN antenna
- There are numerous opportunities for DSN antennas at one of the three DSN communications complexes to support from one to four Cluster spacecraft at a time
- These opportunities fall into a range of priority categories, types of science, and observation durations, and the selected distribution of selected opportunities needs to meet the desired distribution as closely as possible
- Because a high-value Cluster opportunity involving three or four spacecraft will frequently run into contention for use of three or four DSN 34 meter antennas, avoiding contentious regions of the schedule is an important strategy to avoid later disruptions

As a consequence of these factors, a number of tradeoffs emerge when generating a Cluster schedule. For example, schedules with many multi-spacecraft observations tend to run into contentious periods of DSN antenna oversubscription by other users, and so they are vulnerable to disruption. The ability to explore these and other tradeoffs in the schedule is an ideal application of the MUSE approach.

We have adapted the MUSE multi-objective scheduler to the specific problem of generating a one-week Cluster WBD schedule of observations. The decision variables in the problem map to possible combinations of categorized priority and science types among the available opportunities. For example, in order to meet the objectives of a sample of observations of each scientific category, no more than one or two from each category should be considered as candidates at once. Therefore we have developed an encoding of the possible combinations that ensures that conditions like this are satisfied. We have investigated the initial use of four different maximization objectives:

- Collision avoidance: maximize the observation time spent outside contentious periods insofar as they are known in the preliminary DSN schedule
- Spacing: spread out the Cluster observations roughly evenly over the schedule time span
- Total time: maximize the total observing time
- Multi-spacecraft time: maximize the weighted time spent in multiple spacecraft observations, reflecting the fact that, e.g., one 3-spacecraft observation is of greater science value than three separate single spacecraft observations

Figure 8 shows an example population of schedules generated with the prototype Cluster scheduler. The X-Y plot (1) shows the collision avoidance metric vs. multi-spacecraft time, and the tradeoff options are clearly visible. This digram shows two of the four objectives (selected from the lists on the left of the plot), projected from from four to two dimensions. One particular schedule (selected in the crosshairs of the X-Y plot) is shown at the bottom of the window (3), along with the resource consumption of existing activities in the schedule that are competing for the same antennas that Cluster can use (5). The red histograms on the far left (1) show the overall distribution of objective values. The blue histogram subset is selected interactively by the user as a range on one of the charts (2), whereupon the corresponding points in the other objective histograms are also colored blue. In this case, the extreme maximum range of collision avoidance has been selected (uppermost histogram), which "brushes" the other histograms coloring the same points (and highlighting them in the X-Y plot as well). The anti-correlation of collision avoidance and multi-spacecraft time is clearly visible.

The prototype Cluster scheduler has been used so far by the Cluster scheduling team to generate six weeks of operational schedule inputs. The use of the scheduling software significantly shortens the time required to generate each schedule, and more importantly provides the scheduler with confidence that a good schedule has been created, and quantitatively how well it meets the various criteria. The most important remaining challenge for the Cluster domain is that of providing the infrastructure for optimally *revising* an existing schedule as external factors impact the original choices.

5 Conclusions

We have described the MUSE Multi-User Scheduling Environment as an architecture for multi-user multi-objective scheduling. This problem is common to many space science missions and scientific facilities. To elaborate the necessary features and implementation trade-offs, we have adapted this architecture to three different domains: JWST scheduling, Cassini science planning, and Cluster WBD opportunity scheduling. While these adaptations are by no means complete, they have shown the significant promise of our approach, and generated interest on the part of operations teams for these missions as of potential assistance. We plan to make the MUSE adaptations available to these teams, and in one case (Cluster) the software has been used to generate operational schedule inputs.

Future plans include the adaptation of MUSE to additional missions for the purpose of further validating our overall approach, and to provide a framework for broader use. We are also actively exploring other visualization approaches that can be used for higher dimension objective spaces. The combination of improved schedule comprehension and visibility, along with collaborative schedule development, offers the potential for a significant advance in scheduling support for future missions.

Acknowledgments

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