Activity Planning for a Lunar Orbital Mission

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■ *This article describes a challenging, real-world planning problem within the context of a NASA mission called LADEE (Lunar Atmospheric and Dust Environment Explorer). I present the approach taken to reduce the complexity of the activity-planning task in order to perform it effectively under the time pressures imposed by the mission requirements. One key aspect of this approach is the design of the activity-planning process based on principles of problem decomposition and planning abstraction levels. The second key aspect is the mixed-initiative system developed for this task, called LASS (LADEE Activity Scheduling System). The primary challenge for LASS was representing and managing the science constraints that were tied to key points in the spacecraft's orbit, given their dynamic nature due to the continually updated orbit determination solution.*

In this article, I describe the application of artificial intelligence technology to address the challenging problem of activity planning for a lunar orbital NASA mission: the Lunar Atmospheric and Dust Environment Explorer (LADEE).

AI technology can help solve a given problem through a software system that automates some aspect of the problem-solving process. However, often, a significant aspect of the benefit an AI scientist can provide is in terms of defining an effective formulation of the problem and an effective design of the problem-solving process, involving some combination of humans and software.

I present the application of the AI principles of problem decomposition and planning abstraction levels (for example, Nilsson [1971] and Knoblock [1993]) to the design of the LADEE activity-planning process in order to reduce problem complexity. This design saved time and reduced conflicts in servicing the observation requests from the multiple science instrument teams. I also describe the mixed-initiative software system that was developed to make this process efficient enough to meet the mission requirements and time pressures of the tactical workflow. This system is the LADEE Activity-Scheduling System, which we call LASS. LASS was used extensively throughout the mission; it was used by the instrument teams, the project science team, the Science Operations Center planner, and by the mission planning and sequencing team, which was led by the author.

The key challenge in developing LASS was the efficient management of science constraints that were expressed in terms of when the spacecraft was in a certain point in its orbit around the moon. Given that the orbit determination is constantly being updated, the prediction of when the spacecraft would be in a particular point in the orbit changes during the

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overall planning process. Our solution to this challenge is generalizable to apply to other planning problems that have analogous issues.

Before discussing the activity-planning problem and our problem-solving approach, I present some background information on the LADEE mission and its concept of operations to help convey the problem complexity and the time pressures imposed on the planning processes.

Mission Overview

The primary objectives of the Lunar Atmospheric and Dust Environment Explorer mission were to determine the composition of the lunar atmosphere, to investigate the processes that control its distribution and variability, and to characterize the lunar exospheric dust environment. The mission was carried out by NASA Ames Research Center in collaboration with NASA Goddard Space Flight Center.

The LADEE spacecraft launched atop a *Minotaur V* from Wallops Flight Facility on September 6, 2013. The lunar orbit acquisition phase was completed on October 12, 2013, beginning the commissioning phase. This phase included the checkout of the three science instruments: Lunar dust experiment (LDEX), neutral mass spectrometer (NMS), and ultraviolet spectrometer (UVS). All three instruments were attached to the spacecraft in a fixed configuration; hence, to point an instrument required the spacecraft to attain an appropriate attitude. This phase also included a successful technology demonstration of lunar laser communications.

The 100-day science phase of the mission started on November 21, 2013; after a period of extended operations, the mission ended on April 17, 2014, when the spacecraft struck the moon.

The Mission Operations Center was located at NASA Ames in California, and the Science Operations Center was located at NASA Goddard in Maryland. The project scientist and deputy were at NASA Ames, and the three science instrument teams were geographically distributed: the LDEX team at the University of Colorado at Boulder, the NMS team at NASA Goddard, and the UVS team at NASA Ames. The Laser Communication Operations Center was at MIT Lincoln Labs in Massachusetts.

Communications with the spacecraft were accomplished primarily through the deep-space network with secondary support from the near-earth network, as well as the tracking and data relay system during launch and early mission operations.

Mission Operations

Figure 1 presents an overview of mission operations; in this article, I focus on the activity-planning aspects, indicated by the dark boxes. Activity planning was performed throughout all phases of the mission, but in this article, I focus on the primary phase — the science phase, which was nominally 100 days (not counting the extended mission phase). Due to the moon's gravity, in order to maintain the equatorial science orbit, 19 maneuvers had to be performed during these 100 days.

Almost all of the science observations during this phase were executed on board the spacecraft through an absolute timed sequence (ATS). The orbit maintenance maneuvers, as well as other engineering activities, were also executed through the on-board ATS. A number of activities, for example, uploading command sequences or downloading housekeeping and science data files, were executed from the ground through the command plan. A command plan is a computer program run by the flight controller on the command and telemetry ground system in order to guide the interactions with the spacecraft.

Each science observation was implemented through one or more relative timed sequences (RTSs) that were started from the ATS at the appropriate time. For LDEX, the appropriate time was any time that the sun was not in the instrument's bore sight. For NMS and UVS, the appropriate times were defined in terms of where the spacecraft was in its equatorial orbit around the moon. Specifically, the observation times were constrained to occur at some temporal offset to when the spacecraft was crossing one of six orbital points: sunrise terminator, sunset terminator, noon, midnight, umbra entrance, and umbra exit (see figure 2). The most important, with respect to the primary science objectives, was the sunrise terminator, which was when the spacecraft was passing from the lighted portion of the moon to the dark portion of the moon, since the spacecraft was in a retrograde orbit. The science phase orbit was designed such that when crossing the sunrise terminator, the spacecraft would be approximately 50 kilometers above the surface of the moon, in order to satisfy mission requirements. These requirements also specified that various types of science observations had to be performed near the sunrise terminator event every 12 hours.

To determine the absolute time to start an NMS or UVS observation, the times when the spacecraft would cross these six orbit points in the relevant orbit had to be predicted. The orbits were approximately 113 minutes in duration; hence, there were 12–13 orbits per day. Based on tracking data collected roughly every three orbits, the flight dynamics team was continually updating the orbit determination, which is the basis for making these predictions. Based on the spacecraft pointing accuracy requirements imposed by the science instruments, the ATS was updated every other day, using the most recent orbit solution available. Typically, an ATS covered an 80-hour period, where the last 32 hours covered the contingency that the next ATS did not get uploaded in time. When the next ATS included a maneuver

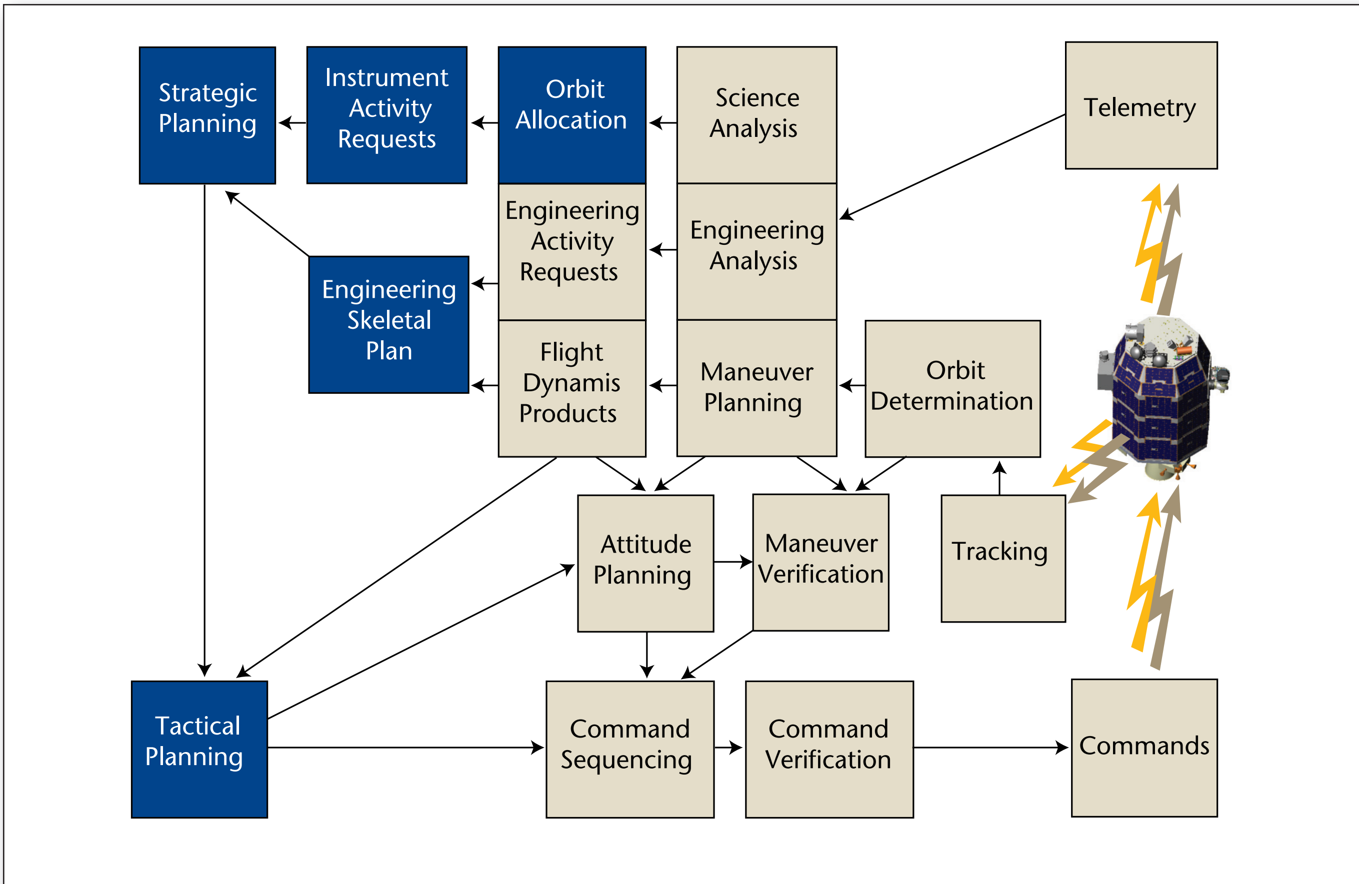

Figure 1. Overview of LADEE Mission Operations.

The five dark boxes involve activity planning.

(always within the second day of the ATS), then an extra 24-hour period was added to the previous ATS to cover the contingency that the maneuver did not take place.

In addition to the 12-hour cadence requirement (mentioned above), there were exclusion requirements on the science observations. No science activities could execute during a maneuver or when using the thrusters to reduce the momentum in the reaction wheels. Typically, two orbits per day were dedicated to communication through the medium gain antenna with the spacecraft attitude fixed to point the antenna toward Earth. During these communication passes, no science activities were allowed. Hence, there were about 10 orbits per day that science observations could be performed, constrained in relation to one or more of the 60 orbit events.

Tracking was collected through the omni-directional antennae with the spacecraft in its nominal attitude, pointing in the direction of motion, called *ram attitude*. Thus, during tracking, any science activity that deviated from ram attitude was not allowed. All of the UVS science activities required attitude changes away from ram, so they were disallowed during tracking passes. LDEX typically operated in the ram attitude and one of the most common types of NMS observations was performed in ram attitude, so these activities could coincide with tracking.

Due to power limitations and attitude conflicts, NMS and UVS were never operated simultaneously, but LDEX could operate at the same time as either NMS or UVS, due to its very low power consumption and its ability to be operated in almost any attitude.

Activity Planning

Activity planning played a critical role in supporting LADEE's concept of operations; the science teams and most of the mission operations teams contributed in some way to the activity-planning process. This process had to accommodate the every-other-day generation of command products (ATS and command plan) in support of real-time operations, the strategic planning of instrument activities, communication scheduling, and maneuver planning, as well as the longer-term planning in support of the high-level science objectives and the overall mission design.

In designing the activity-planning process, there

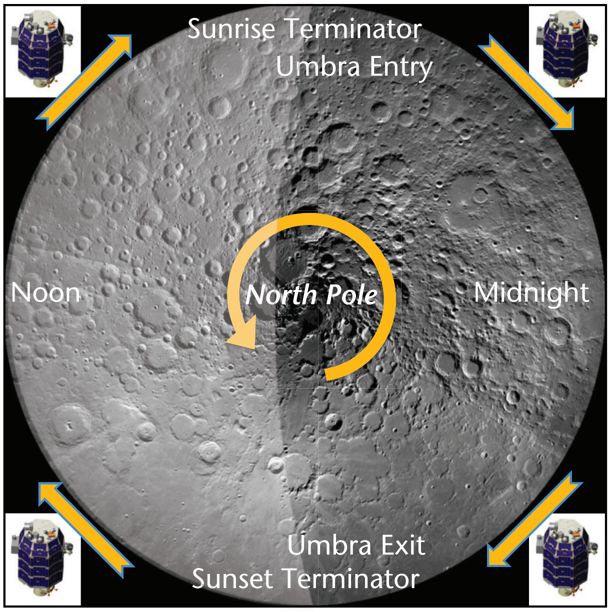

Figure 2. The Six Lunar Orbital Events.

were several key questions to address, including how best to coordinate the geographically separate Science Operations Center and Mission Operations Center; how best to coordinate the geographically separate instrument teams competing for spacecraft time at the key points in the orbits; and how to make the tactical process flow efficient enough to meet the time deadline of the ATS upload while employing an orbit determination recent enough to meet the instrument pointing accuracy requirements.

To address these concerns, we employed the well-known AI principles of problem decomposition and planning abstraction levels (for example, Nilsson [1971] and Knoblock [1993]), and attempted to create nearly independent subproblems, where possible, to reduce complexity.

The resulting design of the planning process had six different types of activity plans, all built using LASS: mission plans, orbit allocation plans, instrument plans, engineering skeletal plans, strategic plans, and tactical plans. The mission planning and sequencing team built the mission plans in coordination with the project scientists, the flight dynamics team, and the system engineering team. The generation of the engineering skeletal plans, orbit allocation plans, instrument plans, and strategic plans were coordinated around the science operations working group meetings that took place twice a week, led by one of the project scientists, with the science planner driving the activity-planning system. The mission planning team generated the tactical plans every other day. Figure 3 illustrates an overview of the activity-planning process.

Mission plans facilitated long-term planning for early phases of the mission and for each month-long lunation of the science phase. Mission plans provided guidance for generating orbit allocation plans and engineering skeletal plans, and they were updated after each maneuver.

The mission plans were constructed so that they satisfied the high-level objectives and mission requirements. They contained the following information: (1) communication station allocations, which indicate when the station was reserved for LADEE; (2) predicted station view periods, which indicate when the spacecraft was able to communicate with the station; and (3) abstract activities, with only approximate start times and durations

An orbit allocation plan allocates orbits, or parts of orbits, to the instruments, based on the content of the appropriate lunation mission plan. Orbit allocation plans are seven days in duration. Like mission plans, orbit allocation plans help monitor and achieve high-level mission objectives, for example, the 12-hour cadence science requirements. The plan incorporates the relevant subset of the current engineering skeletal plan and contains abstract activities, indicating the science instrument and type of observation. Each abstract science activity was constrained with respect to the primary orbit event, based on the observation type. These plans provided guidance for instrument activity planning. More importantly, these plans enabled the instrument teams to generate their requests for spacecraft time independently, without having to worry about what the other teams were requesting.

An instrument activity plan is based on the current orbit allocation plan and represents the team's request of activities to be included in the next strategic plan; it contains detailed science observation activities. A given abstract activity in the allocation plan may correspond to one or more detailed activities in an instrument plan. When the abstract activity corresponds to a set of activities, there are additional temporal constraints with respect to the orbit events, as well as between the instrument activities. Generally, the instrument plan contained the types of observations that were in the allocation plan; however, the teams were allowed to change the type of observation as long as they stay within the temporal bounds of the allocations. These plans are seven days in duration.

During the science phase, the LDEX instrument plan was built differently than for NMS and UVS. Since the LDEX team wanted to operate their instrument whenever the sun was not in its bore sight, the mission planning and sequencing team created the LDEX activities as part of the tactical planning process, based on a flight dynamics product that indicated when it was safe to operate LDEX.

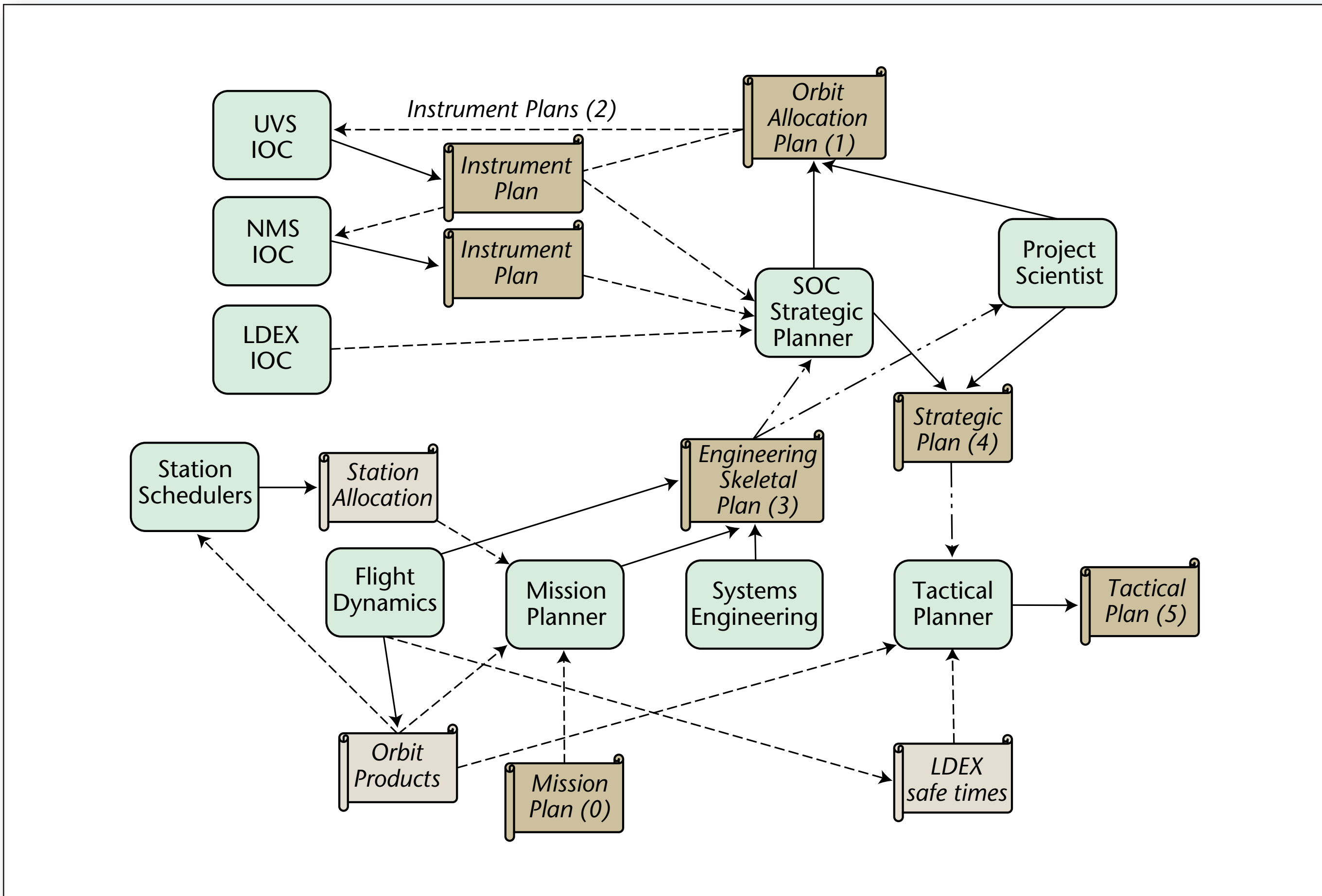

Figure 3. Overview of the LADEE Activity-Planning Process.

The rounded boxes represent mission operations teams; the scrolls represent mission products, where the darker scrolls represent one of the plans: (1) orbit allocation plan (OAP), (2) instrument activity plan (IAP), (3) engineering skeletal plan (EAP), (4) strategic activity plan (SAP), (5) tactical activity plan (TAP).

An engineering skeletal plan is built from the relevant portion of the current mission plan and contains updated station allocations and view periods, as well as any engineering activities that the science teams need to plan around. The plan also contains information needed to support science planning, for example, the predicted times of the key six orbit events (per orbit). These plans are 10 to 11 days in duration.

The science planner used LASS to integrate the NMS and UVS instrument plans with the new engineering skeletal plan to construct the strategic activity plan. This strategic plan was then reviewed at the meeting. The integration may have introduced conflicts due to the updated orbit event times; such conflicts would be resolved during the meeting. The resulting violation-free strategic plan would guide the generation of the next one or two tactical plans. The second part of the meeting would be a review of the next orbit allocation plan, which would form the basis for the next round of instrument planning.

A tactical activity plan was built on top of the relevant subset of the current strategic plan and contained detailed science and engineering activities, as well as their associated temporal constraints. A tactical plan represents what will be executed on the spacecraft and is used to automatically build the command plan and parts of the ATS. Tactical plans have the same duration as the associated ATS (either 80 or 104 hours) and were generated every other day. To convey a sense of the size and complexity of tactical plans, we use the plan for the 11th orbit maintenance maneuver and the plans before and after the maneuver as examples:

The 104-hour premaneuver plan had 1486 activities and 551 user-entered binary constraints.

The 80-hour maneuver plan had 1094 activities and 392 user-entered binary constraints.

The 80-hour postmaneuver plan had 1224 activities and 422 user-entered binary constraints.

The differences between the content of a strategic plan and the tactical plan(s) built from it are due to

1/16/14	1/17/14	1/18/14	1/19/14	1/20/14	1/21/14	1/22/14	1/23/14	1/24/14	1/25/14	1/26/14	1/27/14	1/28/14	1/29/14	1/30/14	1/31/14	2/1/14	2/2/14
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Figure 4. Planning Cadence and Orbit Determination Updates.

(1) Orbit allocation plan (OAP). (2) Instrument activity plan (IAP). (3) Engineering skeletal plan (EAP). (4) Strategic activity plan (SAP). (5) Tactical activity plan (TAP). The gray squares that a plan covers indicate its temporal span; note that a plan is delivered some number of days before its span starts. The dark squares indicate when a new orbit determination (OD) is delivered and the light green/gray squares at the end of a plan's span indicate upon which OD the plan was based. Note, between the creation of an OAP and the associated TAP, the OD is updated three times.

the flight dynamics products derived from the most recent orbit determination. These products included the times of the six orbit events and the station view periods. The activities that were directly or indirectly constrained with respect to an orbit event that had a new start time would have to shift in time in order to keep the constraints satisfied. Similarly, the communication activities may have to be moved or shortened in order to stay within a station view period. These changes in activity start times and durations could cause new conflicts in the plan, requiring further modifications of activity start times or durations, and at times requiring deletion of an activity.

Figure 4 illustrates the activity-planning cadence and how the orbit determination deliveries were used in the construction of the different types of activity plans. The numbers on the left side of the figure indicate the order of plan creation, which is also shown by the dark scrolls in figure 3.

Tactical activity planning was on the critical path in the time-pressured tactical planning workflow, and there was even more to do on days when an orbit maintenance maneuver was to be planned. The sequence in table 1 defines the tactical critical path for the flight dynamics team and the mission planning and sequencing team:

The tactical process was bounded on the right by the time of the communication pass intended for the ATS upload, and it was bounded on the left by the tracking data cutoff time for the orbit determination. Delaying the ATS upload would result in using the contingency portion of the previous ATS, which would yield less accurate instrument pointing. Pushing the tracking data cutoff earlier would also result in degradation in pointing accuracy in the later portion of the new ATS.

LADEE Activity-Scheduling System

Given the complexity of all the activity-planning tasks in the LADEE mission, and given the time pressures of the tactical planning task, it was deemed necessary to employ an automated activity-planning system to increase efficiency and reduce human errors.

We evaluated four candidate systems, three government systems and one commercial system. There were 28 relevant requirements, from which 15 selection criteria were defined. A questionnaire, based on the criteria, was submitted from each candidate development team and used to score each system according to the 15 weighted criteria. Table 2 displays the criteria and the associated weights.

This selection process resulted in the choice of a planning system based on the NASA cross-center,

1.	Tracking data cutoff
2.	Orbit determination
3.	Design maneuver plan.
4.	Derive orbit events and station views
5.	With LASS, generate initial tactical activity plan and attitude profile activity report
6.	Generate tactical attitude plan, attitude constraint violations, and LDEX safe periods
7.	With LASS, finalize tactical plan with LDEX activities
8.	Generate ATS and command plan
9.	Verify command products
10.	Command approval meeting
11.	Upload and start new ATS

Table 1. Tactical Activity-Planning Sequence.

	Criteria	Weight
1.	Provides a facility for modeling science and engineering activities	0.08
2.	Provides a graphical user interface to facilitate activity-plan generation and revision	0.10
3.	Provides a facility to display and edit activity plans and associated information	0.10
4.	Provides an automated facility for detection of flight rule violations	0.10
5.	Provides a mixed-initiative facility for incrementally generating conflict-free activity plans	0.08
6.	Provides a facility for displaying and real-time monitoring of command sequences that implement an integrated activity plan	0.02
7.	Supports the programmatic generation and manual editing of the set of command sequences required to implement an integrated activity plan compatible with the LADEE flight software	0.05
8.	Supports the programmatic generation and manual editing of a command plan to be run by the flight controller in order to execute the integrated activity plan	0.02
9.	Supports the generation of definable command reports, both text-based and html-based, for example, for web browser display	0.02
10.	Maintains continuity between command upload cycles	0.02
11.	Supports interfacing to external systems, including the following: flight dynamics system, ITOS, ground station scheduling	0.08
12.	Provides performance capabilities sufficient to support the LADEE mission, including the following: handles the number of expected activities, allows editing of the plan within the expected response time, does flight rule violation checks	0.1
13.	Supports or has the capability to support security requirements detailed in NPR 2810.1	0.05
14.	System maturity, for example, how many releases and how stable is the product	0.03
15.	Provided by an organization that can support LADEE; includes overall cost	0.15

Table 2. Evaluating Candidate Systems.

component-based Ensemble development effort, and called the LADEE Activity Scheduling System or LASS. Ensemble is a plug-in architecture that is easily customizable for a given application and is based on the open source Eclipse Rich Client Platform. Figure 5 shows an overview of the Ensemble architecture. The LASS development effort took 2.5 years for two full-time people.

The front-end user interface of LASS is a customized version of the Scheduling and Planning Interface for Exploration (SPIFe) that provides a rich environment for creating activity plans, including the five facilities: (1) a broad suite of plan editing tools and plan views; (2) a facility for creating a wide variety of temporal constraints between two activities; (3) modeling and display of numeric and state resources; (4) detection of numeric resource violations (for example, maximum limit exceeded); for each such violation, the user could pick one of the suggested resolutions; and (5) a facility for creating and using activity-plan templates.

The mission domain knowledge is encoded in an activity dictionary that includes definitions of activity types and resources. The LADEE dictionary con-

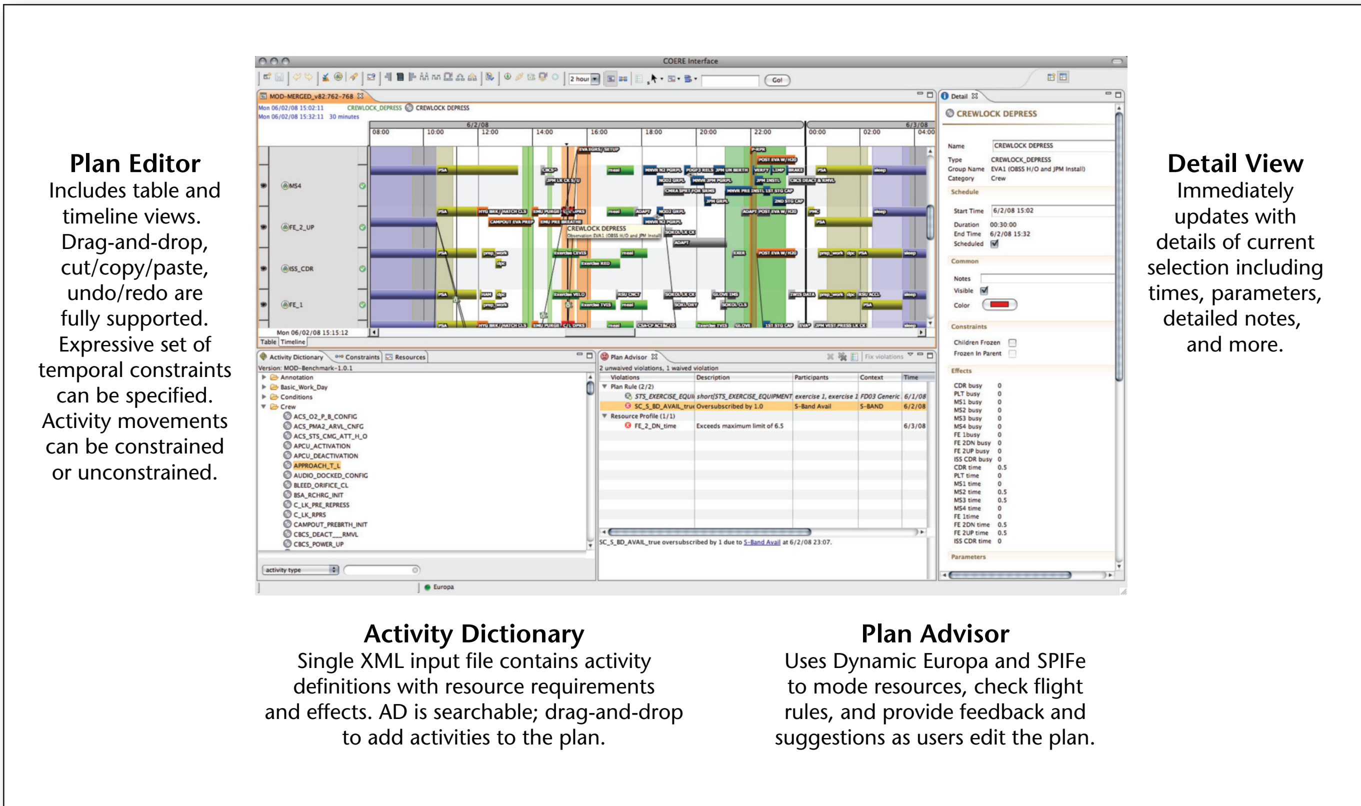

Figure 5: Overview of Ensemble Architecture.

tained 134 activity type definitions. The activity type definitions include parameters and their default values, a formula to compute the activity's duration based on its parameters, the conditions required to perform the activity, and the effects that the activity has on the resources. There are three types of resources: claims (for example, the thrusters and reaction wheels), state resources (for example, station allocations and view periods), and numeric resources (for example, energy budget and consumption). A claim could only be used by one activity at a time. The activity flight rules are automatically derived from all the required conditions and effects specified in the activity dictionary. These flight rules take the form of activity mutual-exclusion rules; that is, they specify which types of activities cannot be executed simultaneously.

Members of the science teams and the mission planning team used the plan template facility extensively. An activity-plan template is a reusable partial plan, consisting of a set of activities and their associated temporal constraints. Templates can be hierarchical, that is, a template can contain other templates. The LADEE template library contained 53 templates.

A new plan-integration facility was added to LASS to enable the merging of two or more activity plans without duplicating the activities they had in common. The science planner used this facility to integrate the UVS and NMS instrument plans with the updated engineering skeletal plan.

LASS includes a back-end, powerful constraint reasoning system, called Dynamic Europa, built with the extendable uniform remote operations planning architecture (EUROPA) (Jónsson et al. 1999). Dynamic Europa detected temporal violations and state resource violations, and it provided a mixed-initiative facility for resolving these violations. The user could either request that all the violations in the plan be resolved or just a selected subset of the plan. The violation resolutions consisted of movement of activities in the plan. The recommended moves would be displayed and the user could accept some or all of the movements; the accepted ones would then be performed automatically. For more details on Dynamic Europa see Morris et al. (2011). Dynamic Europa proved useful in making the tactical activity-planning process more effective, as well as in supporting the creation of valid templates.

Previous deployments of Ensemble had not been applied to an orbital mission like LADEE, so the key challenge in developing LASS was how to manage the science constraints with respect to the orbital events. Both SPIFe and Dynamic Europa could only reason

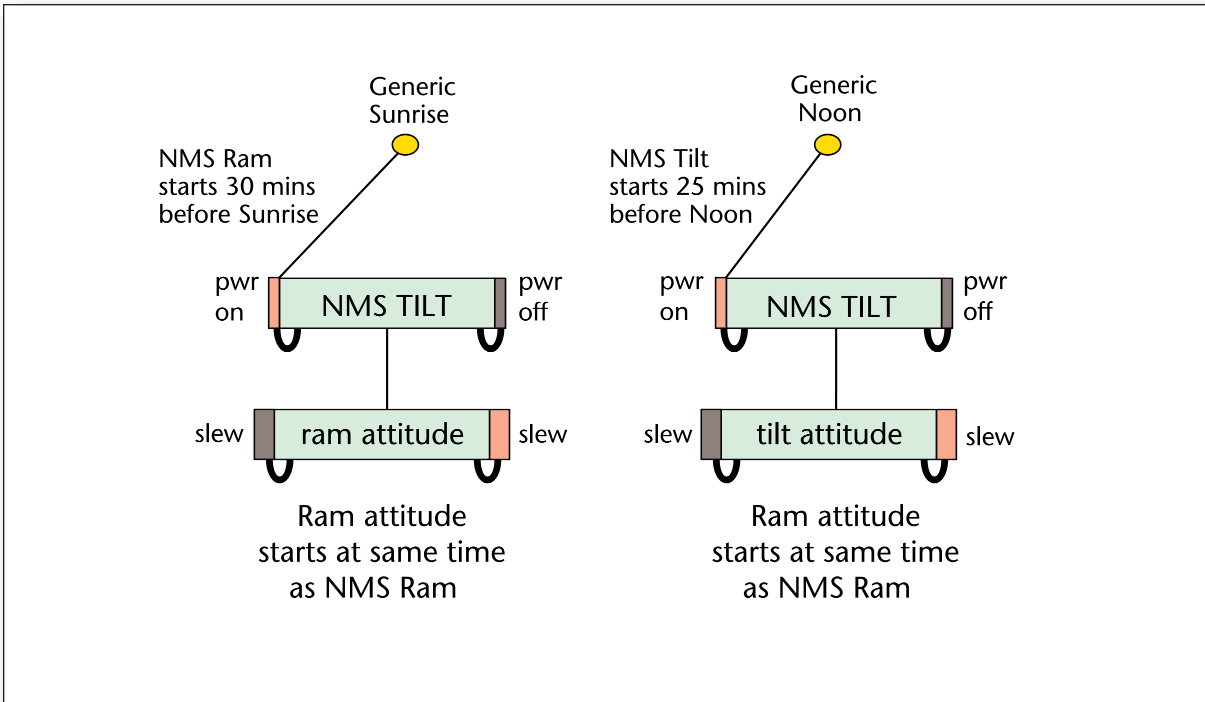

Figure 6. Example Science Observation.

about time, not points in a spacecraft's orbit. An activity could be constrained with respect to a time of day (or a time interval); for example, activity A must start between 10:30:00 January 10, 2014 and 11:00:00 January 10, 2014. In addition, an activity could be constrained with respect to another activity in terms of a relative temporal relationship; for example, activity C must start between 10 minutes after and 30 minutes after activity B ends.

The approach to address this challenge was to convert the orbital-type constraints into temporal constraints between a science activity and an orbital event activity, and to develop new facilities to manage these event activities and associated constraints such that the dynamic nature of orbit determination was accommodated. For a given orbit solution, the absolute times of the six orbital events could be predicted; however, throughout the activity-planning process, the orbit determination was continually updated, and these absolute times could change.

A new kind of activity type was introduced in the dictionary to define the orbital events. Thus, for LADEE, six activity types, of this special kind, were defined in the dictionary. These event activity types had two key parameters: a numeric orbit identifier and a Boolean flag that indicated whether it was a real orbit event or was a generic orbit event. In addition, a special import facility was developed to read in a file, generated by the flight dynamics team, specifying the predictions of the orbit events, per numbered orbit, based on a given orbit solution.

Given a plan without any event activities, the import process for this file type automatically created an event-activity instance for each event listed in the file, with the specified start time and orbit number. These imported event activities had the Boolean flag set to indicate that they were nongeneric (that is, real) events.

In order to constrain a science activity with respect to one of the orbit events, the user would create a generic event activity of the desired type (for example, sunrise) and then create the desired temporal constraint between the science activity and the generic event activity (for example, the science activity must start 20 minutes before the start of the sunrise orbit event). Then, using the new snap-to-orbit mode in LASS, the user would place the pair of activities within the desired orbit in the plan, near the desired real orbit event, and the generic event activity would automatically snap to the associated real event activity (that is, they would have the same start time), and the science activity would move to the appropriate start time to satisfy the temporal constraint.

If a user wanted to move the science observation to a different orbit, the user could just drag the generic event to the desired orbit, and both activities would move to the appropriate start times to reestablish the desired temporal relationships. If the science observation involved several activities with temporal constraints between them, then dragging the associated generic event activity would automatically move all of the observation's activities, as long as there was some chain of temporal constraints from the generic event to each science activity. For example, in figure 6, all science activities are directly or indirectly constrained with respect to one of the two generic events.

A given science template could contain multiple generic orbit events, each constrained to a group of science activities; dragging such a template, from the template library, into the plan would cause each generic event to snap to the nearest real event of the same type, and all the associated science activities would be moved accordingly, so that all the temporal constraints were satisfied.

There was also a new facility to move a group of activities constrained to an orbit event to another orbit by specifying the desired orbit number, rather than dragging the group, but this was rarely used in practice. This facility would be useful to move groups of activities to an orbit far in time, especially if the desired orbit was beyond the portion of the plan within view. Typically, a group of activities was moved to a nearby orbit, so users would, instead, drag the group, using the snap-to-orbit mode.

In order to update the orbit event times based on an updated orbit solution, a new event file from the flight dynamics team would be imported. Given a plan that already had a set of orbit events with start times based on some previous orbit solution, the import process is more complicated. The new events are matched with the current events in the plan based on the orbit numbers, and the matched events are moved to the new start times. This update also moves all the science activities constrained (directly or indirectly) with respect to the moved orbit events, so that all the temporal constraints are reestablished. Performing such an update manually would have been quite a burden on the human planners and would have made it difficult, if not impossible, to meet the tactical deadlines.

LASS-Related Work

The Ensemble effort initially grew out of the experience with two planning tools used on the Mars Exploration Rover mission: the science activity planner (Norris et al. 2005) developed by JPL, and the mixed-initiative activity-plan generator (Bresina et al. 2005) developed by NASA Ames and JPL. Based on the lessons learned on this mission, a number of improvements have been introduced since then; for a discussion of these new developments, see the papers by Bresina and Morris (2006), Aghevli et al. (2007), and Bresina and Morris (2007).

There have been a number of Ensemble deployments for NASA missions involving robotic surface operations, as well as for the International Space Station. The system used on the Phoenix Mars Lander mission was called the Phoenix Science Interface (Fox and McCurdy 2007), the system in use on the Mars Science Laboratory mission is called the Mars science laboratory interface (MSLICE), and the system called Score is used for space station operations. LASS shares a number of plug-in components used in MSLICE and Score and has some unique features that are not in any previous deployments, for example, generalized import and export capabilities and enhanced customization capabilities. Of the Ensemble deployments, LASS is the only one that employed Dynamic Europa to support the mixed-initiative planning process.

Dynamic Europa has heritage from the remote agent experiment on the Deep Space 1 mission (Muscettola et al. 1998). In EUROPA, planning and scheduling are performed at the same time, using an underlying temporal constraint reasoning system to maintain a consistent schedule. There have been a number of systems that are related to EUROPA. A prime example is the automated scheduling and planning environment (ASPEN) from JPL (Fukunaga et al. 1977), which has been deployed on a number of missions in support of mission operations. One of the key differences between ASPEN and EUROPA is the underlying search approach. A related mission operations planning system, from the commercial world, is flexplan from GMV (Barnoy et al. 2009), used for the Lunar Reconnaissance Orbiter mission. A key difference is flexplan's use of production rules for scheduling, plan optimization, constraint detection, and constraint resolution. For a detailed comparison of these two systems, as well as a number of other related planning systems, see the paper by Chien et al. (2012).

Since the successful deployment of LASS to the LADEE mission, an open source version of SPIFe, based on LASS, was created.[1]

Concluding Remarks

This application of the AI principles of problem decomposition and planning abstraction levels to the LADEE activity-planning problem yielded numerous benefits, and serves as a concrete example of how these principles can be applied to other complex problem domains. Due to the orbit allocation abstract plans, the instrument teams were able independently to create their activity plans, representing the requested instrument observations. This use of abstraction planning also reduced the number of plan modifications the science planner had to carry out during the science operations working group meetings, which was important given the geographically distributed science team. Without this abstract allocation approach, the science meeting would have ended up being a much longer, more contentious negotiation process, involving many more plan modifications during the meeting and a greater risk of introducing errors. The project science lead estimates that the duration of these meetings would have been at least three times longer. Thus, this approach saved time, reduced human errors, and caught conflicts among the instrument teams' requests earlier in the planning process.

The science planning team and the mission planning team were able to perform their tasks asynchronously and mostly independently, with activity plans as the primary medium of communication. No member of the mission planning team attended the science meetings and no member of the science planning team was directly involved in the mission planning tasks. The one interface between the two planning teams was the project lead and deputy. At least one of them participated in each meeting, and at least one of them was available at the mission operations center to support the mission planning team, when needed. For example, if the tactical activity plan had to deviate from the strategic activity plan in some significant way, such as deleting or modifying a science observation, then project science would be consulted for advice and approval. Though this imposed additional workload on the project science team, it was much more effective than reopening a negotiation with the three instrument teams during the time-pressured tactical planning process.

Furthermore, employing multiple plan abstraction levels with differing temporal scope helped to satisfy the different levels of mission objectives and flight rules. Planning constraints (for example, science cadence requirements) could be evaluated and addressed much earlier in the process, thus reducing the complexity of tactical activity planning.

The LADEE activity-planning process would not have been possible without substantial automation support. LASS played a key role in making activity planning effective for the many different users (UVS and NMS instrument teams, science planner, the project science lead and deputy, and the three mission planners), and enabled the mission operations team to meet the deadlines imposed on the tactical workflow. The many benefits of LASS derived from both work-saving facilities, such as the widely used template library, and powerful AI technology, such as the constraint reasoning mechanisms that enabled violation detection and mixed-initiative resolution of violations. In addition to making activity planning more efficient, these constraint-reasoning mechanisms played a key role in template creation and validation. Once the instrument teams had developed a solid set of error-free templates, the number of human errors and constraint violations in the science observations decreased dramatically.

The primary innovations to the Ensemble suite of systems that was introduced in LASS were the concept of *orbital events* and the facilities to represent and manage such events. Without these innovations, it would have been difficult to represent accurately the science intent in the various types of activity plans, thus reducing the quality of the science return. Without the automatic plan update mechanism, given a new orbit determination, the user's process would have been much more tedious, error prone, and time consuming. In addition, without this timesaving update mechanism, it would have been quite difficult to meet the tactical workflow deadlines. As the lead tactical planner, my estimate is that the process would have taken at least twice as long; another mission planner estimates even greater time savings. Furthermore, there were times when due to a discovered issue or new information, we had to backtrack in the tactical workflow and regenerate the tactical activity plan and command products. In these cases, without the time-saving mechanisms, we would have had to postpone the upload of the new ATS, thus degrading the quality of the science data and reducing science return.

This approach to managing dynamic orbit events is generalizable and can be applied to problem domains that have events with four characteristics: (1) they play a key role in activity constraints; (2) they occur on a probabilistically predictable schedule; (3) the predictions change and improve over the course of the planning process; and (4) manually updating the plan to account for these changes takes too much time or is too error-prone.

As an example, consider factory-scheduling problems, which could include these types of events. For example, the events could represent a number of daily deliveries of different types of raw materials. If these delivery events impose various constraints on the factory schedule, and if the arrival estimations of these deliveries improve during the planning process, then the delivery events satisfy the four characteristics listed above. Thus, such a problem domain could benefit from the approach we employed.

Future Work

As mentioned previously, an update to the orbit solution would not only cause changes to when the six orbit events occurred, but could also cause changes to the view periods for the communication stations. The change could be significant enough that the associated communication activity would no longer be entirely within the view period, thus requiring the communication activity to be moved and/or shortened. Within LASS, this plan modification had to be done manually. It turned out that these plan updates were required often enough that it would have been worthwhile to develop a way to automate this manual plan modification.

One option would be to apply the mechanism used for orbit events. For example, we could introduce a new event type to represent some point in the moon's orbit around Earth and then constrain the start of each communication activity to an event of this type. This type of approach would address a majority of the issue; however, there would still be a need to shorten some of the communication activities manually.

Another option is to treat this issue as a resource violation and extend Dynamic Europa to be capable of resolving such violations. This type of approach, though more difficult, would have much broader benefit to activity planning because it could address other resource flight rules. After the code base for LASS had been frozen for use in flight operations, the EUROPA framework was extended to address the issue of resource-violation resolution; however, this is still an active area of research.

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Note

1. For more information on OpenSPIFe, see github.com/nasa/OpenSPIFe/wiki.

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