Automated and Adaptive Mission Planning for Orbital Express

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The Orbital Express space mission was a Defense Advanced Research Projects Agency (DARPA) lead demonstration of on-orbit satellite servicing scenarios, autonomous rendezvous, fluid transfers of hydrazine propellant, and robotic arm transfers of Orbital Replacement Unit (ORU) components. Boeing's Autonomous Space Transport Robotic Operations (ASTRO) vehicle provided the servicing to the Ball Aerospace's Next Generation Serviceable Satellite (NextSat) client. For communication opportunities, operations used the high-bandwidth ground-based Air Force Satellite Control Network (AFSCN) along with the relatively low-bandwidth GEO-Synchronous space-borne Tracking and Data Relay Satellite System (TDRSS) network. Mission operations were conducted out of the RDT&E Support Complex (RSC) at the Kirtland Air Force Base in New Mexico. All mission objectives were met successfully: The first of several autonomous rendezvous was demonstrated on May 5, 2007; autonomous free-flyer capture was demonstrated on June 22, 2007; the fluid and ORU transfers throughout the mission were successful. Planning operations for the mission were conducted by a team of personnel including Flight Directors, who were responsible for verifying the steps and contacts within the procedures, the Rendezvous Planners who would compute the locations and visibilities of the spacecraft, the Scenario Resource Planners (SRPs), who were concerned with assignment of communications windows, monitoring of resources, and sending commands to the ASTRO spacecraft, and the Mission planners who would interface with the real-time operations environment, process planning products and coordinate activities with the SRP. The SRP position was staffed by JPL personnel who used the Automated Scheduling and Planning ENvironment (ASPEN) to model and enforce mission and satellite constraints. The lifecycle of a plan began three weeks outside its execution on-board. During the planning timeframe, many aspects could change the plan, causing the need for re-planning. These variable factors, ranging from shifting contact times to ground-station closures and required maintenance times, are discussed along with the flexibility of the ASPEN tool to accommodate changes to procedures and the daily or long-range plan, which contributed to the success of the mission. This paper will present an introduction to ASPEN, a more in-depth discussion on its use on the Orbital Express mission, and other relative work. A description of ground operations after the SRP deliveries were made is included, and we briefly discuss lessons learned from the planning perspective and future work.

I. Introduction

THE Orbital Express satellites were launched on March 8th, 2007 from the Cape Canaveral Air Force Station. The two satellites (ASTRO and NextSat) were in the mated configuration at the start of the mission. The operational concept was to perform a series of increasingly difficult autonomous rendezvous while varying the

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Figure 1. NextSat during an unmated scenario

capture methods, exchanging on-board batteries, transferring flight computers, and performing propellant transfers after the docking process had been completed.

Over the mission lifetime of 135 days, 3000 contacts were executed with a 95% success rate, as many as 45 contacts were executed in a 24 hour planning period, and the dynamic planning process involved had re-planned as many as 4 iterations in a planning period to account for mission anomalies and real-time schedule changes.

II. Planning Problem

A scenario typically consisted of a series of procedures, each of which was written by the operations personnel in Word table format. Each procedure listed its steps and associated durations and represented the need for a contact and the type of contact desired or required. Several procedures had other embedded procedures and some spanned more than one day. As an example, the "unmated" scenario required an initial setup procedure, then the "unmated" procedure would be kicked off; the de-mate, hold, and re-mate would execute, and then a post-rendezvous and capture transfer procedure would be planned. See Fig. 1 for an image of the unmated scenario mid-execution in the "de-mated" configuration.

The schedule of each scenario was dependent on what had been accomplished to date, as the goal of each scenario was to become increasingly more autonomous. The planning schedule was also dependent on the state of the flight system, the amount of preparation time needed before execution, and resources available on future dates. Calendar planning was done by a combination of input from Flight Directors, Mission Managers, Project Management, and DARPA.

Procedures were delivered to the SRP and copied to Excel. An ASPEN (Ref. 1) model-generation script was then used to create ASPEN Modeling Language (AML) representations of the procedures. Once the AML model existed for a procedure, the ASPEN tool read the AML description of the procedure and could be used to add any number of different procedures in a plan required to make up the scenario. Scenario-related resources such as total energy consumption and constraints on the number of contacts used per day could then be managed by ASPEN.

III. The NP-Hard String Assignment Problem

Due to limited hardware and human resources, an interesting planning challenge arose for the SRP and Satellite Operations Center (SOC) mission planner with respect to assigning theoretical "string" allocations to directly support the scheduled AFSCN and TDRSS network contacts.

The SOC had four stand alone strings (unique set of hardware configurations) which were continually available for SOC personnel to support three satellites; the string usage was of concern during the OE mission because it would determine when the other satellite was able to use the resources.

The four strings had a generic set of constraints that were developed as a result of operational testing and performance validation conducted at mission rehearsals prior to launch.

- To support an AFSCN contact, each string required at least 60 minutes prior to Acquisition Of Signal (AOS) for initialization. When the string was done supporting a contact, it needed to be re-initialized to support the next contact (60 minutes).
- To support a TDRSS contact, each string required at least 60 minutes prior to AOS for initialization.
- The string could support up to three TDRSS contacts without being re-initialized if the string were not up for longer than 90 minutes.

Given the described rule set listed above, it is possible to have multiple solutions for a given set of scheduled contacts. For example, consider a list of contacts and their respective times displayed in Table 1. (LOS is Loss Of Signal).

Contact Type:	AOS (UTC):	LOS (UTC):
SGLS	00:00:00	00:15:00
TDRSS	00:15:00	00:45:00
TDRSS	00:45:00	01:15:00
TDRSS	01:15:00	01:45:00
TDRSS	01:45:00	02:15:00
SGLS	02:15:00	02:30:00

Table 1. Sample Contact Times

With the rule set described above, and using the contact times, it is possible to arrange the contacts in the following configurations:

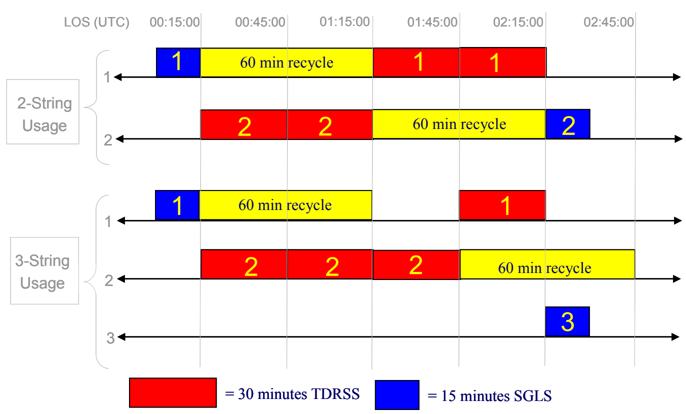

Figure 2: Contact Configurations

There could be a total of 4096 unique combinations in the search space of this problem (otherwise modeled by 4^n, where *n* is the number of contacts) many of which do not meet the established rule set for string assignments.

It can be shown that the hardware resource problem described above is comparable to the Vehicle Routing Problem with Time Windows (VRPTW), a well known integer programming problem that falls into the NP-hard problem classification in computational theory (Ref. 2). It could be considered a variant of the Job-Shop Scheduling problem (Ref. 3) as well as a variant of the Bin Packing problem (Ref. 4).

Because of time constraints and staffing considerations, a greedy algorithm was developed and used to predict resource usage in ASPEN. The results were compared by running the tasking files through two different greedy algorithms developed by the Space Test and Engineering Contract (STEC).

IV. STEC String Assignment Algorithms

The first greedy algorithm was a time variant to the classic bin packing next fit NF method (Ref. 5). Each string was the equivalent to a bin with a one SGLS contact capacity. The contacts in Table 1 would be arranged by this algorithm to be the 3-string usage model in Fig. 2.

The second greedy algorithm was a time variant of the best fit BF bin packing method. Each string was the equivalent to a bin with a 24-hour capacity. Each SGLS contact had a 60 minute time offset. Each TDRSS either had the same offset applied to it or no offset at all. Using this method, the contacts in Table 1 would be modeled by the 2-string usage chart seen in Fig. 2.

The output of the greedy STEC algorithms would provide the specific hardware resource assignments for every pass listed in the tasking file. If the results exceeded the resources available, the contact spacing would be manually examined by the mission planner and then given to the SRP to assist in determining the string assignments and/or modifying the contact times without impacting the mission timeline.

V. ASPEN Introduction

ASPEN is a planning and scheduling tool which reads AML models, places activities on a timeline and determines conflicts in resource allocations and pre-defined constraints. At a high-level, activities can be moved, added and/or deleted in an attempt to fix conflicts. All requirements in the models must be met, and the instances of activities must exist in the plan.

ASPEN was requested by Boeing to be used as the mission operations planning tool for Orbital Express. Once the AML models of the procedures were correct, automation ensured that all plans were correct: that they satisfied the requirements and did not violate constraints. Having models for procedures enabled any unknown variables to be dynamically altered per scenario and allowed flexibility in planning.

The ASPEN repair heuristics or set of choice points during the iterative repair cycle embed decision making processes to facilitate rapid, reliable generation and updating of plans. As resource values changed, which happened on a daily basis on the OE mission, the modification of a plan is automatic. A user of ASPEN can move activities and update resources and the plan changes accordingly. Although the AML models were automatically generated from the procedures, they were often edited due to changes in mission objectives or concepts and/or changes to the goals of the experiment or general activity planning.

During operations of the Orbital Express mission, ASPEN was used to create models of the procedures, which represent data and timing information about the spacecraft and contacts needed for each step, it was also used to create a daily timeline, laying out the steps of the procedure across a 26 hour period. ASPEN tracked limited resources for potential over-subscriptions and ingested changing communication products to reference the most up to date visibility and availability information for the contact networks, Satellite tasking files were then generated, which were used to command the spacecraft. ASPEN also output operation summaries used by the flight team on a daily basis and by the planning team for long-range planning.

VI. Planning Process: Operations Flow

Planning for mission operations had a monthly, weekly, and daily schedule flow. In Fig. 3, a calendar of the planning cycle is shown, where green days represent the long-term planning timeframe of 24 to 7 days out from execution, and the yellow day is the daily planning timeframe: one day out from execution. The red day is execution day, also referred to in operations as the real-time planning timeframe. At long-term planning time, seven

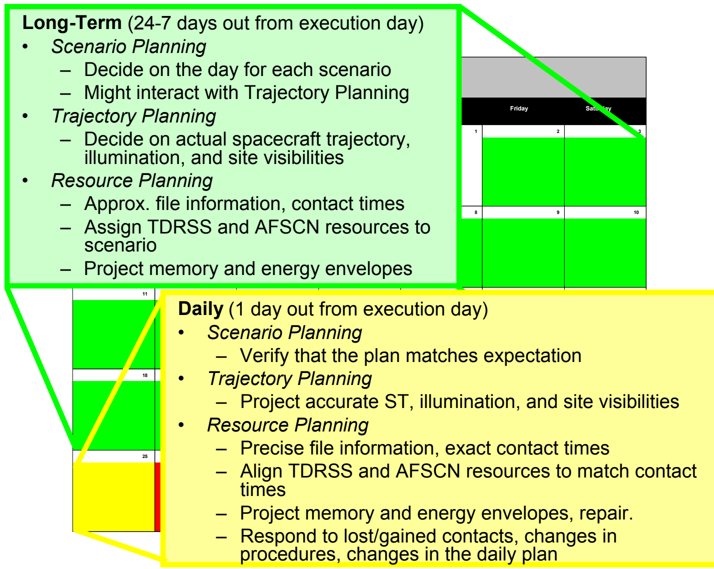

Figure 3. Monthly, Weekly, and Daily Planning Cycle of OE Mission Operations

days of scenarios for the execution week were determined. Some of the scenarios were based on the predicted trajectory data. Procedures were approximated with steps numbers and durations, and the required contacts were assigned. In the beginning of the mission, planning for the TDRSS network was done at long-term planning time; however, over the course of the mission, it was determined more efficient in cost and time to schedule the TDRSS contact times at the daily planning timeframe, except for critical times during the unmated scenarios.

At the daily planning timeframe, if the scenario to be executed had changed from the long-term plan, the new scenario was fit to the existing contacts reserved and any new contacts needed to complete the plan were requested. The SRP then worked with the Mission Managers to determine feasibility of the new plan. Generally any such changes would take place in the long-term planning timeframe of 24 to 7 days outside execution. To accommodate more immediate changes to the scenarios, contacts, and/or procedures, a mid-term planning timeframe was developed during the mission. Daily planning took precedence each day, then any mid-term alterations were addressed, and throughout the week, long-term planning was completed. Verifying the steps of any altered procedure, aligning the procedures to match the newly projected contact times, and responding to any lost or gained contacts was also part of the daily planning process.

The main factors that caused re-planning in the operations planning process were external network de-confliction, procedure changes and/or objective changes to the mission, and the rippling effect of plan changes in a limited mission timeline. Network de-confliction for OE occurred approximately 24 hours before the scheduled planning day. Usually, R&D operations that use the AFSCN, such as OE, run at a lower priority, hence the planning process can be more susceptible to contact rescheduling due to higher priority missions receiving AFSCN resources. For several critical mission times and operations, the OE spacecraft were assigned new and/or higher priority levels for their required contacts.

Procedure changes and/or objective changes to the mission caused the need to re-plan at both the long-term and the daily timeframe. Mission objective changes were mostly due to off-nominal events and could occur during scenario or quiescent operations. Command procedure changes were often made to better represent the energy and memory consumption rates which were learned and more accurately approximated over the mission duration. This could affect the contact requirements to meet mission success criteria.

The mission timeline had an indirect effect on the planning process; an increase in the operations timeline increased project funding. Reduced funding translated into a tighter schedule which increased the quantity of objectives with respect to time. Mission timelines were adjusted based on the successful completion of scenario operations and on-orbit anomalies. Hardware anomalies or flight software resets during rendezvous operations had a ripple effect that would span for several weeks of long-term planning.

Other internal events such as the staffing profiles of Mission Controllers along with hardware resource allocations could also have an effect on the daily planning.

VII. Planning Process: Network Contacts

The two methods of communication for OE were over the AFSCN (or SGLS network) and the TDRSS network. The AFSCN was chosen for the high bandwidth Storage State of Health (SSOH) downloads and immediate commanding needs while TDRSS was utilized for more passive telemetry monitoring and ASTRO commanding. NextSat was limited to communicating through the AFSCN.

Prioritization schemes were used over both the TDRSS and the SGLS networks while the mission was engaged in critical scenario operations and anomalies. ASTRO and NextSat increased their AFSCN contact priorities over commanding and telemetry supports during scenarios.

Projected use of AFSCN and TDRSS supports were critical to review at least three weeks prior to the scheduled execution of a scenario. These three-week projections would drive such planning elements as the Satellite Operations Center (SOC) staffing schedules, other internal mission planning operations, and help with the network prioritization of contacts.

The long-term plan consisted of seven daily tasking files containing all of the desired contact site and times on both the AFSCN and TDRSS network. The objectives, priorities, and the desired commands were all contained in the plan. The one-week collection of plans was typically submitted to the SOC four weeks ahead of execution. The SOC would process the long-term plans and schedule the contacts and associated priorities on both networks.

The mid-term plan would consist of the rest of the AFSCN planning week if the schedule had changed during execution as well as all long-term plans scheduled to execute that had been previously scheduled on the networks. This could range from several tasking files to just over twenty one.

The short-term or daily plan is the final tasking file delivery to the SOC. This file contains all of the SGLS and TDRSS contacts that are to be supported after going through the daily de-confliction process with the AFSCN. Typically, the SRP received the list of contacts to be deleted from the AFSCN around 7:30 AM local time, had approximately a half an hour to decide what supports to change and which additional contacts to request, and delivered a finished plan by 12:00 PM local time.

VIII. Planning Process: Inputs and Outputs

The lower half of Fig. 4 depicts the output products from ASPEN which were then used by different customers. The daily tasking file, an XML file, contained the following information for the SOC to process using its own mission unique software (MUS):

- Contact type (TDRSS or SGLS)
- Station ID (i.e. TDE, GUAM, etc. …)
- Contact start time
- Contact duration
- Objectives to be executed over the contact
- Objective priorities on AFSCN or TDRSS
- Command ID and argument parameters for the contact
- File uploads to be executed during the contact
- Full Contact Plan with all commands and parameters
- Contact Plan Maintenance (upload for the onboard contact schedule)

Once the tasking file was delivered to the SOC, the following products would be generated for on-orbit execution:

- 24 Hour Board (listing of all OE contacts for the 24 hour execution day)

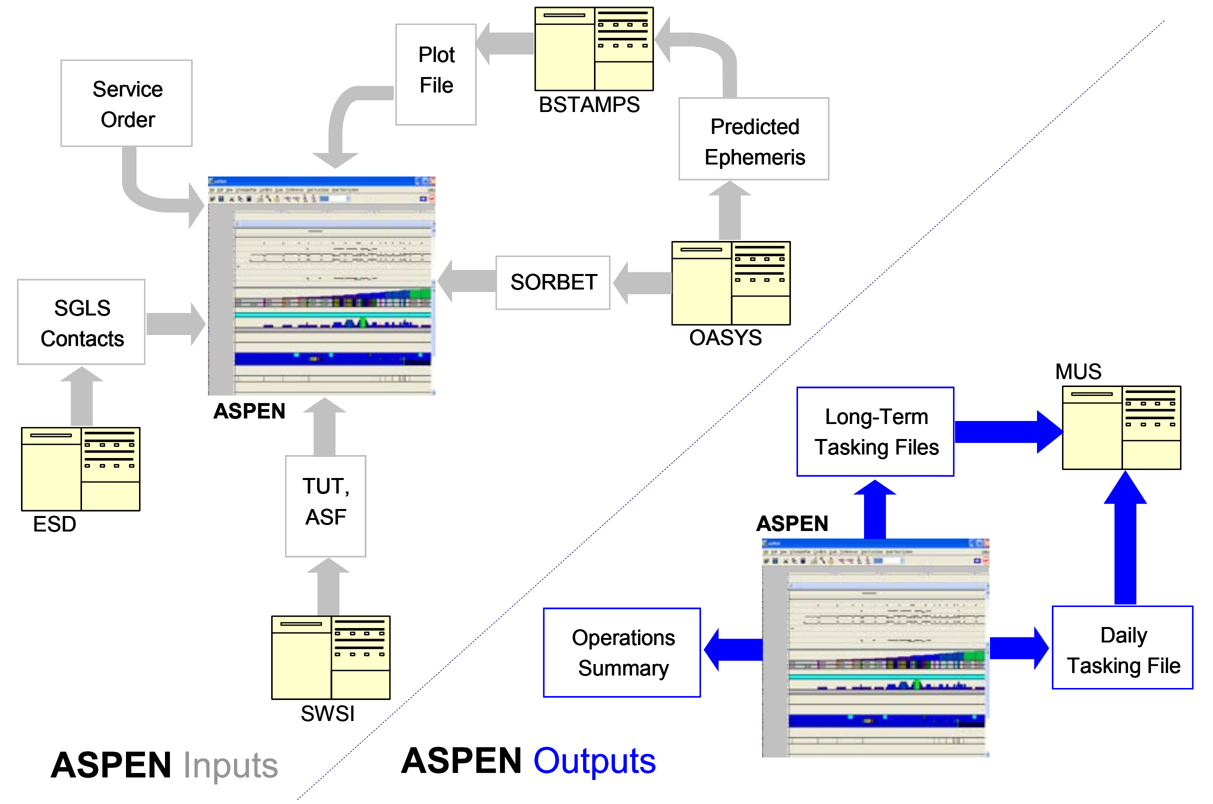

Figure 4. ASPEN Planning Product Inputs and Outputs
ASF (Active Scheduling File), ASPEN (Automated Scheduling and Planning ENvironment), BSTAMPS (Boeing Spacecraft Trajectory Analysis and Mission Planning Simulation), ESD (Electronic Schedule Dissemination), MUS (Mission Unique Software), OASYS (Orbit Analysis SYStem), SGLS (Space Ground Link System), SORBET (Standard ORBit Events Table), SWSI (Space Network Web Services Interface), TUT (TDRSS Unscheduled Time)

- Unique IRON Pass Plans
- Resource String Assignments
- AFSCN Pass Transmit Limits
- Daily Command File (contained all of the built commands in the tasking file that were sent to the spacecraft for the planning day)
- File Uploads (contains all of the upload files that were provided with the tasking file)
- Contact Schedule Maintenance file (NextSat Comm. schedule)
- Contact Plan Maintenance file (ASTRO Comm. Schedule)

ASPEN also output the long-term tasking file. There are no formatting differences between the long-term, mid-term and daily tasking files. The long-term tasking file consisted of a set of seven tasking files which spanned one week. This was processed by the SOC and the resulting output products were:

- String resource allocation schedule
- AFSCN Program Action Plan (PAP)/ Satellite Acquisition Table (SAT) for both ASTRO and NextSat
- TDRSS Batch File
- Spread Sheet of all contacts, mission objectives and pass priorities

A third product, the Operations Summary, was a HTML product which listed all of the information contained in the tasking file in human-readable format. The Operations Summary also displayed all of the steps pulled out from the referenced procedures throughout the planning day.

On a daily basis, the SRP maintained a planning and product delivery timeline in spreadsheet format which was developed to assist daily briefings with the flight directors, orbit analysts, and the mission planners at the SOC. The briefings insured that everyone was on the same schedule and helped coordinate product deliveries between teams. The upper half of Fig. 4 shows how ASPEN ingested mission unique products. The required ASPEN input products and descriptions are described next.

Mission Managers delivered long-term Service Orders to the SRP for each day's plan. The Service Order included specific information about scenarios, including (but not limited to) step numbers in procedures to include or exclude, if such a variation was allowable, numbers and names of files to upload or download, timing information of desired contact strategies, and the high-level overview of the daily mission objectives. The Service Orders were used to create the appropriate plans in ASPEN. When the daily planning process was initiated each morning, the SRP checked the Service Order for any updates to the existing long-term plan. If there were major changes to the Service Orders, the Mission Managers let the SRP know to aid in mid-term planning.

The Standard ORBit Events Table (SORBET) file, which existed in both a long-term and short-term version, was delivered every Thursday to the SRPs and ingested by ASPEN. The Ops SORBET, which spanned anywhere from three days to one week, was the most accurate SORBET, as it was generated from the most recent orbit solution. The long-term SORBET file (or PAP SORBET) spanned 30 days in length. The PAP SORBET was used for long-term planning purposes and provided a good estimate of where ASTRO and NextSat would be if there were no unplanned orbit changes.

The Active Scheduling File (ASF) was delivered to the SRP at the beginning of daily de-confliction. The SRP reviewed the ASF to determine the scheduled contacts on the TDRSS network. After daily de-confliction had occurred, a final ASF was delivered to the SRP to double-check that all requested contacts were fulfilled.

The TDRSS Unscheduled Time (TUT) file was delivered to the SRP every morning. The TUT, a dynamic file which changed by the hour, had to be re-delivered when additional planning and TDRSS pass selections were needed.

The daily de-confliction sheet was also delivered to the SRP every morning along with the TUT and the ASF. The SRP was able to determine which contacts were in conflict with other missions and which contacts had been accepted on the AFSCN.

Two independent orbit analysis (OA) teams were used for operations on the OE program. The first team was comprised of Boeing personnel; the second team was comprised of the on-site SOC personnel. The orbit determination process was started with the on-site SOC personnel using either GPS or ranging data gathered from ASTRO. From the gathered orbit determination data an ephemeris report, the SORBET file, and antenna pointing angles were generated. A 35-day predicted ephemeris report was delivered to the Boeing OA team to integrate into their orbit determination process. After the Boeing team had predicted the orbit and propagated it out approximately 35 days, the SORBET file and the Plot files would feed directly into ASPEN.

Daily and long-term planning files were saved and under version control using CVS on Windows. ASPEN was also used on Windows. Several Perl scripting tools were used in the planning process, and Excel macros were used with scripts to automatically generate the AML models from the procedures.

IX. Planning Process: Post-ASPEN

After the SRP had finished planning with ASPEN, the tasking file and the file uploads were handed to the SOC mission planner. The mission planner, using a tasking file parser, then generated a report similar to the Operation Summary, to manually compare against the scheduled contacts on the AFSCN and on the TDRSS networks. Because the SRP planning process involved hand-editing of deleted and gained contacts, this step acted as a plan "double-check" process. The tasking file parser output a resource usage report as an additional product. This report assigned individual strings to support OE contacts. The resource usage report accounted for string constraints such as a mandatory string recycling time of 60 minutes and the 90 minute continuous TDRSS contact limitation.

After both output products from the tasking file parser were verified and double-checked, the tasking file was ingested by the Tasking Decompiler. The Tasking Decompiler checked that all of the contacts were contained within the specified AOS and LOS times of the AFSCN sites listed in the SORBET file as well as the times listed in the TDRSS Active Scheduling File. After this initial check was complete, the Tasking Decompiler generated the products for execution on-board the spacecraft.

The string profile outputs and the transmit limit outputs were added to the 24 hour board and the pass plans. The transmit limits were autonomously generated using MUS that read the Network Tasking Order (NTO), when it was released from the AFSCN, to obtain specific station sites and sides (specific antenna located at a ground site) for the planning day.

X. Lessons Learned

With a 100% mission criteria success rate, the Orbital Express project proved that spacecraft servicing is a reality for space operations. The goals for the JPL ASPEN team were to model the procedures and constraints of the mission and plan the long-term and daily operations. Using ASPEN and the AML for Orbital Express modeling and planning, the planning team was able to represent mission constraints and procedures. The planning tool was flexible and adaptable to changing parameters.

In the long-term plan timeframe, the plan for the execution day often changed or had several alternatives in one day (the nominal plan versus a backup plan). ASPEN's internal activity structure and quick repair algorithm allowed procedures to easily be shifted from one contact to another and to be deleted and replaced by new procedures without major re-working of the plan. Daily planning was adaptable to changes in which procedures and their associated ASPEN models were updated by operations the day of planning. The auto-generation of models allowed the planning team to share new procedure information and process it quickly for use on-orbit. It also allowed the decision of using a procedure on a given day to be made last-minute and not cause delay on the mission schedule. Models could be generated during the daily planning process and used the same day to plan the execution day's contacts.

Originally, NextSat contacts were not going to be scheduled using ASPEN, however, the simplicity of adding objectives to contacts with the planning tool, NextSat's low-maintenance strategy, and the ease of use for the SRPs to add the activities in ASPEN showed the ability to plan for multiple satellites, and account for many real-world factors in planning operations.

XI. Future Work

Continuous Activity Scheduling Planning Execution and Re-planning (CASPER), an extension to ASPEN, provides a continuous cycle of decision-making capabilities for real-time scheduling, repair and optimization. ASPEN has been successfully used as a ground planning system for earth-orbiting missions on both Orbital Express and EO-1 (Ref. 6). On the EO-1 satellite, the embedded use of CASPER allowed flight operations to achieve higher levels of automation as well. While the EO-1 project is on-going, ASTRO and NextSat completed their end-of-life maneuver and were decommissioned on July 22, 2007 (Ref. 7).

Future mission operations goals for ASPEN include the execution of research currently in development and the implementation of models for new missions. The OASIS project uses CASPER to plan and schedule activities for its rover. The rover then executes the plan and uses the optimization cycle in CASPER to monitor science opportunities and repair conflicts that arise (Ref. 8). A similar use of CASPER is in development for aerial vehicles, or aero-bots (Ref. 9), and for surface and under-water vessels. ASPEN is also currently being researched and used as a tool to schedule and coordinate resource allocations of ground antennas for over 60 missions of the Deep Space Network (DSN) (Ref. 10). Similarly to Orbital Express, continuing work on automating satellite operations is being considered for the DESDynI project using an ASPEN hybrid being built for compressed, large-scale activity planning (Ref. 11, 12).

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