Preparing Cassini Uplink Operations for Extended Mission

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The Cassini-Huygens Mission to Saturn and Titan, a joint venture between the National Aeronautics and Space Administration, the European Space Agency, and the Italian Space Agency, is conducting a four-year, prime mission exploring the Saturnian system, including its atmosphere, rings, magnetosphere, moons and icy satellites. Launched in 1997, Cassini began its prime mission in 2004. Cassini is now preparing for a new era, a two-year extended mission to revisit many of the highlights and new discoveries made during the prime mission. Because of the light time delay from Earth to Saturn, and the time needed to coordinate the complicated science and engineering activities that take place on the spacecraft, commanding on Cassini is done in approximately 40-day intervals known as sequences. The Cassini Uplink Operations team is responsible for the final development and validation of the pointing profile and instrument and spacecraft commands that are contained in a sequence. During this final analysis prior to uplink to the spacecraft, thorough and exact evaluation is necessary to ensure there are no mistakes during commanding. In order to perform this evaluation, complete and refined processes and procedures are fundamental. The Uplink Operations team is also responsible for anomaly response during sequence execution, a process in which critical decisions often are made in real-time. Recent anomalies on other spacecraft missions have highlighted two major risks in the operations process: (1) personnel turnover and the retirement of critical knowledge and (2) aging, outdated operations procedures. If other missions are a good barometer, the Cassini extended mission will be presented with a high personnel turnover of the Cassini flight team, which could lead to a loss of expertise that has been essential to the success of the prime mission. In order to prepare the Cassini Uplink Operations Team for this possibility and to continue to develop and operate safe science and engineering sequences, a review and major update of the current documentation and operations procedures was needed. This paper will address the changes made to extended mission sequence generation processes primarily due to new restrictions in spacecraft operating capability and lessons learned from prime mission. In addition, it will address the state of the prime mission operations procedures, the philosophy changes and updates that were made to those procedures in response to process improvement, and the validation of those new procedures through the training of current and new personnel. And lastly, it will address the lessons learned throughout prime mission and how the Uplink Operations team chose to incorporate those lessons into the working documentation and team knowledge. This incorporation was necessary to facilitate the success of the extended mission with potentially all new personnel at some point prior to the end of the mission.

Nomenclature

AACS	=	*Attitude and Articulation Control Subsystem*
ASI	=	Italian Space Agency
CIRS	=	Composite Infrared Spectrometer
DSCAL	=	Deep Space Calibration

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ESA = European Space Agency
IEB = Instrument Expanded Block
ISA = Incidents, Surprise, or Anomaly
GUI = Graphical User Interface
MAPS = Magnetosphere and Plasma Science
NASA = National Aeronautics and Space Administration
ORS = Optical Remote Sensing
SOP = Science Operations Plan
SSR = Solid State Recorder
SSUP = Science and Sequence Uplink Process
ULO = Uplink Operations

I. Introduction

A. Cassini Mission Overview

THE Cassini-Huygens Mission to Saturn and Titan, a joint venture between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Italian Space Agency (ASI), is nearing the end of its four-year, prime mission exploring the Saturnian system, including its atmosphere, rings, magnetosphere, moons and icy satellites. During its prime mission, Cassini has uncovered some amazing discoveries about the Saturnian system. These discoveries include the determination of two new rings and several new moons orbiting the planet, bringing the total number of known moons to 63. One of the main objectives of the prime mission was to perform a detailed mapping of Saturn's largest moon Titan. This included landing a probe on its surface, which was successfully accomplished in January 2005 when the ESA Huygens Probe descended through the thick atmosphere taking measurements during its descent and during its first moments following the landing. This rich set of Titan data is being used to determine whether conditions on the moon were or are conducive to the development of life. In some of the most recent discoveries, another moon, Enceladus, has been imaged with plumes of water ice spewing from its south pole. Four additional flybys of Enceladus are planned for 2008 to better understand why these plumes exist and how they might relate to the possibility of life on this satellite.

To conduct this scientific exploration, the Cassini spacecraft is armed with a suite of 12 instruments that can be used collaboratively to measure the magnetosphere, dust particles, ring composition, surface topography, atmospheric composition and surface and atmospheric temperatures. This suite of instruments includes 6 In-situ observation instruments to conduct Magnetosphere and Plasma Science (MAPS), 4 Optical Remote Sensing instruments (ORS) to study the electromagnetic spectrum of Saturn and its rings and moons, and 2 microwave remote sensing instruments, a Radar and Radio Science, both of which use radio waves to map atmospheres, determine the mass of moons, collect data on ring particle size, and unveil the surface of Titan.

1. Prime Mission Resource Utilization

The 4,685 pound, 22-foot high by 13-foot wide Cassini spacecraft began its tour with 885 watts of power from radioisotope thermoelectric generators, 130 kg of hydrazine fuel and four reaction wheels, in addition to the main engine, to navigate its orbital operations in the Saturnian system. Cassini transmits its data back to Earth for approximately nine hours each day utilizing its X-band transmitter and high gain antenna. Cassini has been very conservative in its use of consumable resources. As of February 2007, Cassini had used only 25% of its onboard hydrazine, 75% of its main engine bi-propellant and oxidizer, and 30% of the Reaction Control System thruster cycles allocation, with a redundant set of unused thrusters. This gives Cassini adequate fuel resources to continue its navigation of the Saturnian system during an extended mission.

With a mission as complex as Cassini's, which has included demanding navigation to maneuver the Saturnian system, a complex attitude control system to point the instruments, and a distributed sequence development and operations system, it is very fortunate no major hardware failures or commanding errors have occurred to threaten the continuation of the mission. However, there have been a few minor hardware problems including loss of the Ka-Band Transmitter, Solid State Recorder (SSR) memory corruption, the degradation of the Reaction Wheels (RWAs), the Magnetospheric Imaging Instrument's low-energy magnetospheric measurement system motor failure, and the Magnetometer Instrument's Cassini Vector/Scalar Helium Magnetometer failure. Fortunately, most of these hardware components are either not prime or had accomplished most of their objectives prior to the failure. Other minor issues have involved the Cosmic Dust Analyzer and Ion and Neutral Mass Spectrometer instruments having processor timing problems, which have been resolved with either flight software upgrades or a power cycle to the instrument. Also, the Composite Infrared Spectrometer (CIRS) instrument's Deep Space Calibrations (DSCAL) were affected by noise in the reaction wheels at certain speeds. This was resolved by incorporating an additional negotiation process into the development cycle to perform a trade on how best to accommodate CIRS DSCAL quiescent spacecraft needs and the MAPS instrument campaign RWA pointing needs.

B. Extended Mission Overview

A two-year extension has been approved for Cassini mission operations beginning on July 1, 2008. This Equinox Mission includes 60 orbits of Saturn, 43 flybys of Titan, 7 flybys of Enceladus, and 3 flybys of other icy moons. Science objectives for this extended mission include further Enceladus south polar terrain and composition mapping, Enceladus plume thermal and variability studies, Titan weather and atmospheric characterizations, volcanic and cratering studies, a solar ring plane crossing during the Saturnian Equinox of 2009, and a MAPS periapsis campaign to map the magnetosphere and capture the evolution of plasma flows and particle distribution functions as a function of radial distance, latitude, and local time during a relatively short period.

In addition to the Equinox Mission, an additional extension known as the Solstice Mission is currently being planned. In order to protect the aging hardware and remaining consumables required to conduct both of these extended missions, the operations team must continue to negotiate trades between spacecraft resources and science objectives.

Operationally, the main challenge comes with the aging RWAs. The wheels are degrading with time. Due to excessive drag one wheel has been designated for backup use only and is turned on only periodically for lubrication. The overall trend has been towards more drag (metal to metal contact) at the nominal rpm range, which if not alleviated will cause damage and ultimately failure. To deal with this critical issue an iterative process was added to the sequence development cycle. The objective of this process is to find a solution that is acceptable to the health of the RWAs and maintains the science objectives. However, the process is very iterative and solutions are often difficult to find. Also, the process often requires multiple pointing changes and the addition of several unplanned bias activities to return the wheels to an acceptable rpm, which help by shortening segments and removing prediction errors. These biases also use additional hydrazine, a monitored consumable resource for the mission.

Currently these changes are worked late in the development process, affect multiple science and engineering teams, which can pose health and safety risks to the sequence due to the necessity of making changes very late in the process. Several new restrictions have been levied to help reduce risk and hopefully help find design solutions more easily. Some of these include breaking the sequence into smaller, more manageable segments, increasing the rpm range from 300 to 400, enforcing slower turn rates, adding bias activities after flybys to clear up prediction errors, and enforcing an offset about the X-axis for multi-rev turns to reduce external torque/drag.

The Cassini Equinox mission, as currently envisioned, will perform basically the same science and engineering activities as the primary mission, utilizing its operations team as staffed during the prime mission. As the Cassini operations team extended mission budget was not reduced from that of the prime mission, no descope of the planned operations for the extended mission operations was necessary. Therefore, the operations team took the opportunity to look at the current activity planning and command generation process and implement improvements to the sequence development process in response to its prime mission experience. The intention of these improvements is to refine the process flow, handle critical resource issues (such as RWA health and safety) earlier in the process, capture critical lessons learned during the prime mission, update the team procedures and interface agreements, and adequately document critical knowledge necessary for continued mission success.

II. Extended Mission Planning

A. Approach to Extended Mission Preparations

Among the issues that can arise during extended mission operations are outdated procedures, loss of expertise due to high personnel turnover, and a lack of documentation of the collective knowledge based on the prime mission experience. These resource deficiencies often lead to insufficient training of new operations team members. Also, budget cuts that reduced staffing are generally expected and often lead to shortcuts in the documentation of process changes, including updates to the operations procedures, as well as an increasingly lax attitude toward following the procedures due to the view that it is "business as usual." Cassini could face many of the same risks as it enters its first extended mission phase.

So far Cassini has been fortunate enough not to undergo the traditional budget cuts for its first extended mission phase. The operations team took this opportunity to focus on operations areas that needed improvement. In an effort to apply the systems engineering "V" model practices to an operations environment, Cassini adapted the systems engineering development practices to apply to the operations environment. The phases of this practice include Concept Definition, Requirements Analysis, Functional Analysis and Synthesis, Integration and Verification Planning, System Development Process, Operations Team Integration and Verification, System Acceptance, and Operational Test and Evaluation.

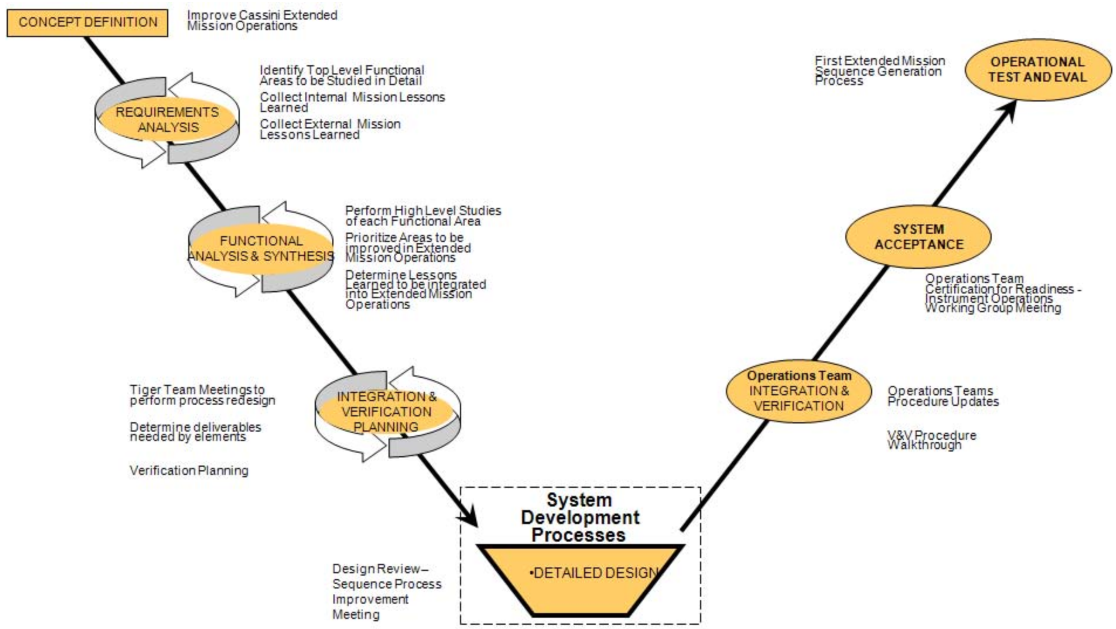


Figure 1. Cassini Extended Mission Planning & Systems Engineering "V" Diagram

Concept Definition

Systems Engineering Personnel were chartered to perform analysis of current mission operations processes and identify and implement improvement where needed.

Requirements Analysis

Formal requirements analysis was not performed as part of extended mission systems engineering. Proper "shall statements" were not constructed and stored in a central requirements database. Rather than undergoing this formal process, Cassini collected lessons learned from a number of sources including internal operations teams, as well as external missions that were currently in or had completed extended mission phases. From these lessons learned, a list of candidate areas that could be further studied and improved were identified. This list included:

- Reaction Wheel bias strategy process location in the timeline
- Determining if the length of our command sequences should be shortened or lengthened
- Refining the Sequence Generation Process
- Updating/Creating new Software for Extended Mission
- Coordination between primary instrument pointing designs ("prime") and secondary instrument pointing needs ("rider") on the same observation
- Revisiting our process to allocate unused data volume before sequence execution
- And, replenishing Ground System Hardware used to develop operations products

In response to the lessons learned from other project extended mission phases, an additional requirement for extended mission preparation was to ensure that all procedures were up-to-date.

<u>Functional Analysis & Synthesis</u>
The functional analysis and synthesis phase included high level trade studies conducted in each of the candidate areas identified above. This process resulted in a prioritization for areas to focus on during extended mission planning. These areas were the sequence generation process and software updates.

<u>Integration & Verification Planning</u>
A Tiger Team was formed to further investigate improvements needed for the sequence generation process. Because the updates were made to essentially the same process structure that had been employed in various phases during cruise and prime mission, it was decided that formal verification and validation was not necessary. In order to validate the process changes, a process walkthrough was held with all of the operations team representatives that concluded that the process and the procedure changes were adequate. In addition, it was stated that the first sequence in which the updated process would be employed would be seen as the formal test and evaluation period of this process, and changes could be made at the completion of that period.

<u>System Development Process</u>
Formal development of the process was done by implementing the process updates on the integrated sequence development schedule. A design review was conducted by all members of the Tiger Team and the managers of the operations team to certify that the implementation was done correctly.

<u>Operations Team Integration & Verification</u>
After the integrated schedule was reviewed and published, operations teams had two months to update their internal processes and procedures in reaction to the updates. At the conclusion of those team procedure updates, a formal procedure walkthrough was held, stepping through each milestone in the integrated schedule, along with each corresponding step in the team procedures. This ensured full coverage of all process changes and team interactions.

<u>System Acceptance</u>
In addition to the operations teams in charge of leading the sequence generation process, the instrument teams and subsystems needed to approve the process changes, and certify that they had adequate hardware, software, and procedures to support extended mission.

<u>Operational Test and Evaluation</u>
The operational test and evaluation process is currently being performed on Cassini through the development of the first extended mission sequence. This development process is considered a trial run through the updated process. The process updates will be reevaluated based on lessons learned during this trial run.

B. Sequence Process Improvement Team

1. Prime Mission Sequence Development Process

For the Cassini prime mission, observation planning and sequence development began two years before the spacecraft began its tour of Saturn. This extremely complex process involved extensive timeline negotiations for seconds of optimum science opportunities, especially around critical flybys. Due to the nature of the spacecraft design, there was also extreme contention for pointing control. The initial spacecraft design included a scan-platform for the ORS instruments and a rotating palette for the fields and particles instruments. However, due to budget cuts, these features were removed from the design, which ultimately complicated the operation of the spacecraft, especially the pointing design process. This resulted in the creation of an extensive, complex pointing negotiation process where multiple instruments negotiate the pointing attitude in order to accommodate more than one observation at a time.

This development consisted of five main phases, the first four led by the Science Planning Team and the final phase led by the Uplink Operations Team. These processes are Science Operations Plan (SOP) Integration, SOP Implementation, Aftermarket, SOP Update, and the Science and Sequence Update Process (SSUP). The main planning period began 20 weeks prior to uplink to the spacecraft in which the early implementation plans for the a sequence period were revaluated and flushed out into a complete, safe and flyable sequence. Because these plans were developed far in advance of the planned execution period, an update process was required to incorporate changes resulting from changes in spacecraft performance and/or new operational constraints.

SOP Integration

During this early process, resources were negotiated, including observation time, spacecraft pointing, power, data volume, and telemetry modes, by multiple working groups each designated by specific science objectives. The products from this process included an integrated time-ordered listing of activities and their resource negotiations in the activity planning database, as well as a wrap-up package noting any significant liens or negotiations.

SOP Implementation

This process assimilated a number of integrated segments to produce the first look at the activities in one sequence. The main objectives of this planning cycle were to resolve any conflicts that arose while integrating multiple segments together, and to develop the initial pointing commands. The pointing commands and the review products associated with them were shelved at the end of this period until closer to the actual execution. Because SOP Implementation was completed prior to the start of prime tour or concurrently with tour sequence development and execution, two sequences were implemented concurrently.

Aftermarket

This update process was a month long period of resource renegotiation that resulted in a new integrated timeline and wrapup package similar to those developed in the SOP Integration period. This process involved the science objective working groups defined during SOP Integration to incorporate their knowledge and experience of the past trades and agreements.

SOP Update

This update was a five-week period during which changes were made to the pointing profile and instrument commands to accommodate the renegotiated resources and begin resolving any remaining resource conflicts. One official review of those products was conducted, and the results of that review, along with the command files, were handed off to the final planning phase.

SSUP

This final process was a 10-week development phase in which the final, low-level, detailed commands were added, thorough and complete flight rule checks were performed and formal approval was given for uplink to the spacecraft.

2. *Prime Mission Lessons Learned*

Each team involved in prime mission activity planning and command generation submitted lessons learned and recommendations for process changes. One particular area that became a challenge during the prime mission was protecting the reaction wheels, part of the Attitude and Articulation Control Subsystem (AACS), from excessive stress during pointing changes. As stated earlier, close attention was paid to the health and safety of the three prime wheels. An impromptu process to evaluate the pointing profile with respect to the reaction wheel rate was developed and inserted into the prime mission sequence development process. The reaction wheels required a bias management strategy and a tool was developed to manage wheel performance and reduce damage under conditions such as low rate dwell durations and high rate spikes. This analysis took place at a point in the sequence development process where the pointing profile had already become stable. The solutions offered to protect the RWAs, however, often caused pointing changes so late in the process that the integrity of the sequence was threatened.

Changes in the extended mission sequence planning and implementation processes were made based upon lessons learned. Additional guidelines and constraints were incorporated in the science integration process to reduce wheel performance impacts and additional time was allocated to finding bias solutions in the implementation process. Changes were made by setting new policy, changing procedures and in some cases by modifying software to implement the new policy. Two notable changes have been to reduce turn rates for turns greater than 60 degrees, and to add a bias during every downlink to reduce wheel degradation. The operations team is just beginning to exercise these changes. They will know if these strategies work to reduce wheel damage after the first sequence in extended mission begins to execute.

3. Extended Mission Sequence Development Process

A Tiger Team comprised of operations team members from Uplink Operations, Science Planning, Spacecraft Operations, and Systems Engineering was formed to explore the changes needed to the sequence development process as a result of extended mission differences and lessons learned during prime mission. This team met every other week for one year, and completed the study in August, 2007. A survey of the science instrument operations team was conducted to understand what operations products they were utilizing during development and what products could be made available in order to improve their process. The resulting process changes include the following:

a. Deletion of the Aftermarket and Update Process

This process is not needed since advanced development of extended mission science sequences did not occur. Instead, the process goes from initial resource negotiation to basic command generation and into the final, detailed development phase.

b. Extended Initial Command Generation Phase

Pointing changes late in the sequence development phase can cause a mismatch between primary and secondary instrument pointing and spawn a series of last minute sequence changes and/or real-time commands to resolve problems found late in the development process. During the prime mission, this issue was occurring more and more frequently due to pointing changes required to protect the health and safety of the reaction wheels. One of the lessons learned from the prime mission is that the pointing profile needs to stabilize much earlier in the development process to prevent major, last-minute sequence changes, most especially pointing changes. To allow for earlier pointing profile stabilization the initial command development phase has been extended from 5 weeks to 14 weeks. During this extended time frame additional pointing profile analysis has been added to uncover reaction wheel heath and safety threats early, thus allowing for renegotiation before additional commands are added to the sequence, which may be dependent upon these decisions. Moving this analysis earlier in the development cycle also allows the team to make the desired changes using a less formal negotiation and paperwork driven process, which is always required during the final, detailed development phase.

c. Increased Overlap During Handoff Between Teams

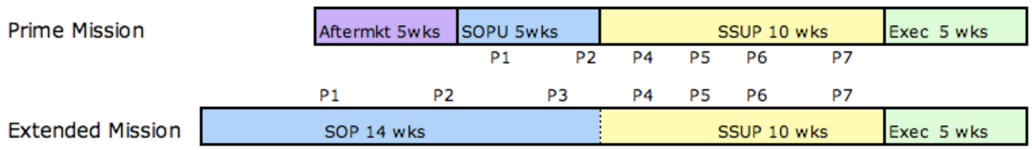
Another lesson learned as a result of this study was that there was approximately one week of dead-time between the final two phases during which no significant work was taking place. This week occurred during the handover between the two teams leading the sequence development process. In reaction to this, the last week of the initial command generation phase and the start of the final command development phase now overlap.

Development control, during this period, is now collaborative between the Science Planning Team and the Uplink Operations Team. Clear roles and responsibilities have been established to ensure key steps in the process are not dropped as a result of this overlap.

d. Review Product Refinement

It was critical to understand what products were needed at different phases of the process in order to complete analysis or continue with sequence development. In some cases teams were given very little time to turn around analysis or incorporate products into their final production. Time was increased, where needed, to allow teams the time required to incorporate products into their final sequence development, without any added workforce stress. Another realization from the study was that multiple teams were creating the same review products as part of their individual flight rule and sequence checks. As part of the Extended Mission process, these products are now officially released earlier in the development process, by the team responsible for generating them, so all of the teams have the advantage of reviewing the same ”official” product in addition to reducing their workload.

A comparison of the two processes can be seen in the graphics below.



Sequence product input ports indicated above on process timelines for both prime and extended missions.

Port definitions:

P1 - Initial pointing designs

P2 - Prime and Rider coordination

P3 - Reaction wheel bias strategy implementation

P4 - Perform any additional pointing and health and safety changes

P5 - Simulation

P6 - Final input port for pointing and health and safety changes

P7 - Contingency port for health and safety only

Notable differences:

1. Prime mission is missing P3, which in extended mission is dedicated for making pointing changes to protect the health and safety of the reaction wheels.
2. More time is given to developing pointing designs in SOP.
3. Time between P1 and P2 is lengthened to perform flight rule checks making output products from P2 more robust and ready for reaction wheel health and safety evaluation.
4. Border between SOP and SSUP is fuzzy in extended mission due to processes overlapping and reducing unproductive time.

Figure 2. Comparison of Prime and Extended Mission Sequence Development Processes

C. Software Updates

Software was modified to incorporate new policy changes documented in the Mission Plan and to increase efficiency and reduce errors. New operational power modes were developed based upon knowledge of subsystem power usage in prime mission and the fact that some opmodes would not work in extended mission. Slower turn rates were implemented for turns greater than 60 degrees in an effort to minimize reaction wheel damage.

A new turn margin policy was implemented based on a study of the actual turn margin used in the 25th sequence of the prime mission. For prime mission, turn margin estimates were based upon statistical analysis of the spacecraft location uncertainty due to orbit trim maneuvers. Spacecraft location uncertainties became much smaller than estimated as new knowledge of the Saturnian system from the early part of the mission was fed back into the navigation process. The turn margin was found to be grossly overestimated in the 25^{th} sequence for ~99.5% of observations. When predicted turn durations were used, the turn margin required ranged from 2 to 11 seconds. The turn margin policy allocated 10 seconds to 9 minutes of turn margin, sometimes increasing the total turn time by a factor of 3. For extended mission, turn margin will range from 10 seconds to 2 minutes depending of the characteristics of the turn. This is still a very conservative model, however, it does conserve deadtime around observations.

New automation software was also created to easily create calendar data for the sequence implementation processes. As processes are refined and schedules change, the new calendar data can be generated quickly, easily and accurately. This greatly reduces a manual and iterative process performed by three operations teams.

III. Uplink Operations Extended Mission Planning

A. Overview of the Team

The Uplink Operations Team (ULO) is the team that leads the final stage of the sequence development process, which includes low-level command development and final flight rule checks. The ULO team is nominally the final authority on the decision of what is safe to be uplinked to the spacecraft. For each sequence two members of the team are responsible for leading the process, with additional help "as needed" from the Uplink Operations Manager. These team members work together to build and validate the set of commands (sequence) that will be uplinked to the spacecraft. Additional functions in this process include sequence simulation in the testbed for critical and/or first-time events as well as the development of the Instrument Expanded Block (IEBs), which include information loaded into instrument memory prior to the start of sequence execution.

The ULO team has been in charge of building and validating the sequence commands for the Cassini Mission since the Launch phase. During the early phases of the mission, including Launch, the Jupiter flyby, Cruise Science and Saturn Approach Science, much of the activity planning was completed by the Mission Planning and Science Planning Teams. Much of this planning was accomplished using manual processes, as the automated activity planning software used later in the Prime Mission did not yet exist. As a result of the premature front-end processes, the bulk of the command generation and validation was placed on the ULO team.

In response to this allocation, the ULO team developed a series of approximately 50 procedures and checklists as well as a number of automated scripts to help them execute the sequence development process more effectively and efficiently. An overview of the team's tasks was represented through the SSUP schedule; one schedule for each sequence development period. Each schedule was a 7-10 page document that outlined the tasks for each work day/hour of the 10-week development process. While this schedule was intended for use by the entire development team, its primary focus was on the ULO team responsibilities. The procedures were mainly a set of formal checklists used by the ULO team to either guide or verify each step in the development schedule. Automated scripts were developed to aid in detailed product comparison and official error checking. Key scripts included parsing error and warning messages generated by the modeling software, summarizing the statistics of the command/sequence file (size, memory location, etc.) and breaking the integrated sequence product into individual subsystem products for subsystem/instrument team verification and/or further command development. Team checklists only existed as a set of bulletized, informal reminders of things that had caused problems during sequence development in the past.

As the Cassini Project neared the start of its prime tour, 50% of the tour phase ULO team members had been on board since Launch or the very early mission phases (~6 years). These team members relied heavily on their experience to perform much of the sequence development process. As a result, the team procedures and checklists were not thoroughly updated at the start of the prime mission. In addition, most procedure changes and updates and any new items needing to be added to the team checklist(s) were generally discussed in staff meetings or distributed via email, but not formally added to the formal documentation or procedures. As each sequence development process came to a close, lessons learned were documented in the associated sequence approval package. Often, these lessons learned were not reviewed until the close of the next sequence development process and had to be re-communicated through team correspondence and at times were missed altogether. The process of gathering the latest information and staying up to date was a burdensome one that relied on repeating information, in addition to each team member having to pay close attention to every sequence development cycle. While this process may have run smoothly during the early phases of the Cassini mission it became a tremendous challenge during the Prime mission as sequence development and execution became much more complex.

B. Process Changes

In addition to the sequence development process changes identified in the previous sections, there were also some internal team changes that affect the process.

The first had to do with uplinking the IEBs, which cannot be uplinked until after the final sequence products have been developed and must be on-board the spacecraft prior to the start of sequence execution. IEBs are a set of commands loaded directly to the instrument memories that can be accessed throughout sequence execution. They allow the memory required to store each sequence to be significantly reduced. The uplink of these files are completed during one to three, very time constrained, uplink passes. Early in the prime mission, it was discovered that the sequence memory can be corrupted if an IEB is being loaded to the instrument's memory from the SSR at the same time as a swap from the prime SSR to the backup SSR occurs (i.e. when the playback of the prime SSR is complete – the prime SSR playback pointer hits the prime record pointer – at this time there is a switch to the backup SSR for record and playback to keep from overwriting data on the prime recorder). In addition, the memory readouts that are used to validate the IEB load can also be corrupted if they occur at the same time as a change in the playback data bitrate. These two issues resulted in a complex procedure that involves calculating the estimated times of the SSR swap and timing the uplink of the file with the one-way lighttime delay (~70-90 minutes), the estimated SSR swap time and the planned playback data rate changes. The sequence specific IEB procedures are formally archived in the event of an anomaly during the uplink process.

The second involved process changes made in response to anomalies discovered in the method of executing some of the software tools the ULO team used to build the final sequence products. Some of these included running the modeling tools using the Graphical User Interface (GUI) rather than in batch mode, as the runtime errors (caused by command syntax errors, etc) were not being logged via a batch run, and defining the sequence uplink windows within the GUI rather that as an source input file. This allows the user to see the expansion of all the sequence commands and clearly identify the sequence beginning and ending times correctly. In addition, all of the configuration files, except for the configuration file used to generate the binary uplink product, were being created by an automated operations tool. This left a vulnerability in the process because this configuration file did not receive the same review as the all of the configuration files used to generate the products, which are the input to the creation of the binary uplink product. After an error was made in this configuration file it was added to the automated operations tool so that the configuration files used in the generation of the binary uplink files received the same review as all other configuration files.

C. Tools

In response to the inefficiencies in documentation and necessary process changes identified during Prime Tour operations, extended mission preparation was a welcome opportunity to change the philosophy of team documentation and communication. This new philosophy includes much-needed updates to the formal procedures, implementation and use of a team website, and the development of a number of new scripts, which automate several of the more tedious, time consuming, and error prone tasks.

One of the major changes to the extended mission sequence process was the consolidation of the SSUP schedule. Rather than relying on multiple steps in the schedule to define the broader tasks, a process overview was created. The overview not only defines the steps involved, it also provides context for what other team members are doing concurrently as well as how they rely on specific products at a given point in the process. In addition, this overview procedure provides a link to the specific, detailed team procedure(s) for each step. The advantage of the process overview and the concise schedule over the detailed, lengthy schedule, is that all of the necessary information is now provided in a more user friendly format that benefits all teams involved in the development process.

The team procedures, interface agreements, checklists, templates, lessons learned, and other team documentation will become part of the team website so that they can be more readily accessed and utilized by all team members. The website will become the location to look for links to the most up-to-date documentation. For the first time since the early mission phases the team procedures are being reviewed and updated to reflect the current and planned future mission operations practices. To help maintain the procedures and documentation a process is being developed whereby at the end of each sequence development and execution period any new changes and/or lessons learned will be incorporated into the official documentation, which is accessible via the website. If followed, this should mean that procedures, interfaces, and tools will remain up to date and easy to locate, as well as provide a suite of formal documentation to aid in the training of new personnel.

Lessons learned were previously documented in the sequence approval package rather than a central location. In this new process, they will now be maintained in a central repository, accessible via the team website, and updated as part of each sequence development period, thus allowing for information to be shared from the originating sequence development and execution period to all future periods.

Lessons learned can originate from a variety of issues, including what are termed Incidents, Surprise, or Anomaly (ISAs). These ISAs can also include spacecraft anomalies that occur during sequence exectution. Generally, these are not captured in any team specific documentation. However, there are times when some aspect of an ISA affects the sequence development process and should be captured in the lessons learned, which may translate into an update to a procedure, script or tool or the generation of an entirely new procedure (such as that described above for the IEBs), script or tool.

In addition to the procedure updates, a number of automated scripts and tools have been developed to ease the tediousness of some of the error prone team processes. These include a script to automate the IEB uplink timing, taking into account SSR swap timing and data rate changes, a script to list the input files used to create the final sequence products to ensure nothing is forgotten, a script to strip out individual subsequences from the final products to make late changes, and a script to include manually generated notes into the graphical sequence timeline based on the actual event times in the sequence.

D. Training

Currently, the training plan for extended mission is the same as for the prime mission. New ULO team members view a set of videos explaining key sequence development software. Each new individual is paired up with an experienced team member and completes two sequences, first as an assistant, executing the software tools, and then as the lead, performing the coordination functions including running meetings and approving sequence and real-time commands. An optional exercise for future team members would be to validate the updated procedures that have been developed by using them in their training. This has not been performed yet, as new team members were brought on prior to the completion of these procedures.

IV. Conclusion

The Cassini Operations Team is prepared to conduct the Equinox mission. This mission will conduct the same level of science and engineering activities as the prime mission, using the improved sequence development process. It has learned from the prime mission experiences and has adapted its processes to accommodate changes to spacecraft resources as well as recent operational complexities. The team performed an update to all of its procedures, not only to adapt to process changes, but also to ensure that information is kept up-to-date in anticipation of staffing changes that are common during extended mission operations.

Despite updates to the sequence process and team procedures, the Cassini Mission still faces many challenges. The Reaction Wheel sensitivity continues to grow, plaguing the operations team with increasing science and engineering trades that must occur during the sequence development process. Additional policy changes are underway to enforce finalization of all science pointing commands during the Implementation phase so that the integrity of the sequence products are not jeopardized close to uplink. Interdependencies between the final pointing profile and subsequence commands continue to be identified. While the systematic approach taken to study the sequence process and identify changes beneficial for the extended mission was solid, perhaps more heuristics should have been applied. One that seems relevant to the current situation is the “Keep It Simple, Stupid” (KISS) heuristic. As the operations team begins its transition into extended mission, the actual operation of the aging spacecraft hardware will only increase in complexity; the orbital dynamics will remain challenging and the scientists’ desires will continue to be demanding. Even without a budget cut that could have reduced staff, it would have been beneficial for the operations team to assume it would “not” be able to continue its current level of science planning and science return, especially in light of the increasing operational challenges.. The Equinox Mission planning process would have been an appropriate place to begin simplifying the process and expectations of the operations team capabilities. This reduction in staffing and science return is currently only being considered for the Solstice Mission.

For the ULO team, the formal procedure updates and the philosophy changes to incorporate lessons learned into a dynamic living document provide the tools necessary for current and new team members to perform their tasks effectively and efficiently. The move toward increasing automation simplifies much of the work, thus allowing the team to focus on management of the more complex issues that arise often during sequence development and execution. From the ULO team perspective, the preparation completed for extended mission will be essential for the continued success of safely and effectively operating the Cassini spacecraft.

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