Launched on October 15, 1997, the Cassini-Huygens spacecraft began its ambitious journey to the Saturnian system with a complex suite of 12 scientific instruments, and another 6 instruments aboard the European Space Agencies Huygens Probe. Over the next 6 ½ years, Cassini would continue its relatively simplistic cruise phase operations, flying past Venus, Earth, and Jupiter. However, following Saturn Orbit Insertion (SOI), Cassini would become involved in a complex series of tasks that required detailed resource management, distributed operations collaboration, and a data base for capturing science objectives. Collectively, these needs were met through a web-based software tool designed to help with the Cassini uplink process and ultimately used to generate more robust sequences for spacecraft operations.

In 2001, in conjunction with the Southwest Research Institute (SwRI) and later Venustar Software and Engineering Inc., the Cassini Information Management System (CIMS) was released which enabled the Cassini spacecraft and science planning teams to perform complex information management and team collaboration between scientists and engineers in 17 countries. Originally tailored to help manage the science planning uplink process, CIMS has been actively evolving since its inception to meet the changing and growing needs of the Cassini uplink team and effectively reduce mission risk through a series of resource management validation algorithms. These algorithms have been implemented in the web-based software tool to identify potential sequence conflicts early in the science planning process. CIMS mitigates these sequence conflicts through identification of timing incongruities, pointing inconsistencies, flight rule violations, data volume issues, and by assisting in Deep Space Network (DSN) coverage analysis. In preparation for extended mission operations, CIMS has also evolved further to assist in the planning and coordination of the dual playback redundancy of high-value data from targets such as Titan and Enceladus.

This paper will outline the critical role that CIMS has played for Cassini in the distributed ops paradigm throughout operations. This paper will also examine the evolution that CIMS has undergone in the face of new science discoveries and fluctuating operational needs. And finally, this paper will conclude with theoretical adaptation of CIMS for other projects and the potential savings in cost and risk reduction that could potentially be tapped into by future missions.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>CIMS</td>
<td>Cassini Information Management System</td>
</tr>
<tr>
<td>TWT</td>
<td>Target Working Team</td>
</tr>
<tr>
<td>OST</td>
<td>Orbiter Science Team</td>
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<tr>
<td>DSN</td>
<td>Deep Space Network</td>
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American Institute of Aeronautics and Astronautics
Figure 1. The Cassini spacecraft and Huygens probe during assembly
I. Introduction

The Cassini-Huygens Project is a joint NASA/ESA/ASI robotic spacecraft mission that arrived at Saturn on July 1, 2004 and was gravitationally captured following a Saturn Orbit Insertion (SOI) maneuver. Over a four-year Prime Mission, the Cassini orbiter was designed to study the diverse Saturnian System including the vertical structure, the horizontal motions, and lighting present in Saturn's atmosphere. Additionally, Cassini has studied the mysterious moon Titan specifically, Titan's surface topography and composition, internal structure, atmospheric composition and processes. Cassini has also spent time investigating the composition, size distribution and physical processes of the Saturn's dynamic rings. And finally, the surface geology and composition, internal structure, and physical processes taking place on icy satellites are also in the process of being investigated.

Laying the foundation for this effort was the Cassini Information Management System, or CIMS. Originally, CIMS was a science planning and resource allocation database. Over time, in the face of the complexities associated with distributed operations, evolving requirements, the unique event-driven science of the Saturnian system, and variety of spacecraft instrumentation, CIMS was used to actually guide the flow of the science planning process. In the following sections, we will discuss the wide array of the instruments on Cassini, the multi-staged sequencing process, the distributed operations on Cassini, and how CIMS plays a central role in tying all of those elements together.

1. Cassini Instrumentation

To achieve this incredibly diverse collection of scientific objectives, the Cassini Orbiter was designed and developed with twelve (12) on-board instruments each working jointly, creating a synergy of valuable information which is used to further our knowledge of the Saturnian System. For the purpose of Optical Remote Sensing (ORS), Cassini is equipped with four groups of instruments:

**Composite Infrared Spectrometer (CIRS)**
The CIRS instrument senses longer wavelengths than the other ORS instruments. As with VIMS, it is used to map the color properties of the atmospheres of Saturn and Titan, the surfaces of the moons, and the rings in order to study their composition and temperature. Principal Investigator: Dr. Michael Flasar, NASA Goddard Space Flight Center

**Imaging Science Subsystem (ISS)**
ISS performs multi-spectral imaging of Saturn, its rings, Titan, and the other moons. Camera images also provide context for other remote sensing investigations and help navigators keep the spacecraft on course. Team Leader: Dr. Carolyn Porco, Space Science Institute

**Ultraviolet Imaging Spectrograph (UVIS)**
UVIS senses shorter wavelengths, in the ultraviolet spectrum. It actually consists of four instruments that take spot measurements and low resolution images of the atmospheres of Saturn and Titan in order to study their structure, chemistry, and composition. Principal Investigator: Dr. Larry Esposito, University of Colorado

**Visual and Infrared Mapping Spectrometer (VIMS)**
VIMS, which is sensitive to the visible and infrared wavelengths, creates maps of the color properties of the atmospheres of Saturn and Titan, the surfaces of the moons, and the rings in order to study their composition and structure. Team Leader: Dr. Robert Brown, University of Arizona Lunar and Planetary Laboratory

Cassini is also equipped with two Microwave Remote Sensing Experiments that broadcast microwave radio signals either to Earth through an occulted target or towards an object where the reflected signal is collected and processed either by the spacecraft or back on Earth.

**Cassini Radar (RADAR)**
Cassini’s High Gain Antenna broadcasts a microwave radio signal which is able to penetrate
Titan's thick atmosphere. The echo of the broadcasted signal is used to produce images, topographic and compositional maps of the surface of Titan, as well as the other moons. It can also penetrate to deeper levels within Saturn’s atmosphere than any other instrument. Team Leader: Dr. Charles Elachi, Jet Propulsion Laboratory

**Radio Science Subsystem (RSS)**

Radio broadcasts from Cassini radiated to Earth through the rings and the atmospheres of Saturn and Titan can explore finer structures of those targets. Doppler tracking of the spacecraft also constrains the masses and gravity fields of Saturn’s moons. Team Leader: Dr. Arvydas Kliore, Jet Propulsion Laboratory

Finally, there are six in-situ instruments that Cassini uses to sample the particles, ions, and magnetic field in the local environment at any given time. Collectively, these are referred to as the MAPS (Magnetic And Plasma Science) instruments. To be effective, these instruments require that Cassini visit as many locations in the Saturnian system as possible at different times to investigate temporal and spatial variations, at different orientations. Each instrument is sensitive to particles of varying mass, charge, and speed although there is overlap in sensitivity for redundancy.

**Cassini Plasma Spectrometer (CAPS)**

CAPS collects plasma (or ionized gas) and measures the composition, density, speed, and temperature of high energy particles throughout Saturn's magnetosphere. Principal Investigator: Dr. David Young, Southwest Research Institute

**Cosmic Dust Analyzer (CDA)**

CDA consists of two sensors, one that counts the number of particles impacting it each second (with saturation at 10,000). The other determines the flight direction, impact speed, mass, and chemical composition of ice and dust particles. Principal Investigator: Dr. Eberhard Grün, Max Planck Institut für Kernphysik

**Ion and Neutral Mass Spectrometer (INMS)**

INMS detects neutral atoms as well as positively charged ions. It collects material and determines the compositions and isotopic abundances of chemicals and elements in the upper reaches of Saturn's and Titan's atmospheres and throughout the tenuous E ring. Team Leader: Dr. Hunter Waite, Southwest Research Institute

**Dual Technique Magnetometer (MAG)**

The magnetometer experiment is used to map the strength and direction of Saturn's magnetic field and interactions with the solar wind. Principal Investigator: Dr. Michele Dougherty, Imperial College, London

**Magnetospheric Imaging Instrument (MIMI)**

MIMI consists of three instruments, two of which measure the composition, charge, and energy of energetic ions and electrons. The third is a remote sensing instrument that produces an image of the charge distribution and composition of the ions in Saturn's magnetosphere in order to study the structure of the magnetosphere and its interaction with the solar wind. Principal Investigator: Dr. Stamatios Krimigis, Johns Hopkins University Applied Physics Laboratory

**Radio and Plasma Wave Science (RPWS)**

RPWS measures the electric and magnetic fields, electron density, and temperature in the interplanetary medium and within the Saturn magnetosphere. Principal Investigator: Dr. Donald Gurnett, University of Iowa

Note that the Principal Investigators, Team Leaders, Co-Investigators, and Ops Support personnel for these twelve instruments are located at ten different institutions in five different countries and eight States.
in the United States. In the next section we will discuss the Cassini distributed operations paradigm and the need for a centralized collaborative database.

II. Cassini Distributed Operations

For Cassini, the distributed operations paradigm was born out of the complexity associated with the Cassini Mission Objectives and the desire to outsource science operations to reduce costs \(^1\). The Cassini Mission Objectives were complex due to the uniqueness of each event (be it a flyby of Titan, icy satellite, or Saturn periapse) and as a result, there was a drive to optimize every observation. The lead-time for optimizing these requests started as much as 3 years prior to execution \(^5\). This need to optimize each observation requires additional time because the observations are designed with greater complexity. Distributed operations also had the added benefit of bringing research and educational institutions into the space exploration fold.

As discussed by Cheng and Larsen, 2006, this choice to implement a distributed operations paradigm was successful on Cassini because of the decoupled nature of these subsystems including the distributed nature of the spacecraft architecture \(^1\). Each science instrument has a unique processor, which is independent of the spacecraft central processor (called the CDS). The CDS serves as a router for the instrument commands and data collected which is then written to the solid-state recorder (or SSR) on-board the spacecraft. The pointing, however, is coupled

In addition to the decoupled nature of the Cassini architecture, the difficulties associated with distributed operations have also been abated because of the non-real-time strategy of the spacecraft commanding.

The Distributed Ops teams participate in each of the 7 phases of the Cassini Ops process:

1. **Tour Selection**
    A Tour is a reference trajectory or the path that the spacecraft will follow around Saturn. Using high-level science objectives, Mission Planners and Tour Designers developed several tours, each with unique characteristics and a particular scientific emphasis. Tours are evaluated and after extensive discussions by the Cassini Science Community, one Tour is selected.

2. **Segmentation and Integration**
    The chosen Tour is then segmented into periods of time determined by the proximity to specific targets in the orbit, Saturn Periapse, Rings, Magnetosphere, Titan, Icy Satellites, and Cross-Discipline. These periods of time are then discussed amongst unique groups called Target Working Teams (TWTs) and Orbiter Science Teams (OSTs) who specialize in the particular target of interest. Agreements are made for a particular period between the members of that group, and those agreements are captured and integrated into a conflict free Time Ordered Listing of commands. This process is called Integration.

3. **Implementation**
    Once the segments have been integrated, they are merged into a sequence, which is then checked for pointing design constraint violations. Additionally, the sequence telemetry profiles, power and data volume envelopes are verified to be violation free. The implementation phase produces a Spacecraft Activity Sequence File (or SASF).

4. **On-the-shelf**
    The Spacecraft Activity Sequence File is then archived or put “on-the-shelf”.

5. **Aftermarket**
    Approximately five months prior to execution, the sequence is taken off the shelf and segmented back to the Target Working Teams for additional integration. This allows teams to revisit previous agreements and make modifications based on new discoveries.
6. **Science Operations Plan (SOP) Update**

Once the teams have had a chance to reintegrate the segments, the sequence is reimplemented in a phase known as the Science Operations Plan (SOP) Update. During this phase, changes which occurred during Aftermarket are verified and validated in the context of a sequence.

7. **Science and Sequence Update Process (SSUP)**

During this final phase prior to uplink, all remaining issues and conflicts with the sequence are resolved and real-time commands required for proper sequence execution are generated. At the completion of the SSUP phase, the sequence is radiated to the spacecraft.

Each of these phases requires input and collaboration from the distributed ops teams and culminates in one “merged” sequence that has been verified and validated before uplink to Cassini. CIMS provides a means for that collaboration.


**III. The CIMS Structure**

The Cassini Information Management System (CIMS) is an intuitive web-based tool with which the distributed operations teams can collaborate and submit specific requests for observations into a centralized database. A request is a set of information from one team that spans a period of time in which one or more activities will be taking place. Figure 2 shows a partial list of requests in a sequence as they appear in CIMS. Each request that is entered by the scientists contains most of the information required to generate, evaluate, and negotiate the timeline (e.g. pointing, power, data volume). There is some additional negotiation that must take place by looking at the pointing design as well. Sequences are typically composed of 1000+ requests and science requests make up approximately 2/3rds of the total requests in each sequence. Requests include the following types of information:

1. The instrument name
2. Primary and Secondary Body Vectors (e.g. What we are looking with)
3. Offsets about those vectors in degrees
4. Primary and Secondary Targets (i.e. What we are looking at)
5. Request begin, duration, and end time
6. Orbit number around Saturn (increments at each Apoapse)
7. Data volume needed for the request
8. Request classification (e.g. Prime vs. Rider which will be discussed in section IV)
9. Power requirements for the request
10. Description of the activity or science taking place
11. Configuration Management Information (e.g. requester ID, request change, justification, etc.)

Figure 3 shows a partial example of one such request. In this example, the request has been submitted by UVIS who will be observing a star at a Right Ascension and Declination of 205° and –53.5° respectively on Day-of-Year 110 at 09:40 spacecraft time and for a duration of 5 hours and 10 minutes.

CIMS stores this information in a database which has been adapted for Cassini and enforces complex relationships on the stored information°. These complex relationships, which will be discussed in section IV, involve the enforcement of a set of rules and policies, that have originated from Mission Guidelines and constraints, on each of the requests as well as rules on the interrelationships between those requests.

In addition to the science requests, CIMS also stores engineering and spacecraft configuration requests for which it also enforces a different set of complex rules and relationships with other requests. These relationships will also be discussed in section IV. Types of engineering and spacecraft configuration requests include:

1. Deep Space Network (DSN) station allocations
2. DSN maintenance downtime periods
3. Pre and Post Calibration times for the DSN
4. Downlink Data Rates and Orientations
5. OpModes and OpMode transitions (i.e. Operational power modes that define a power envelope for the spacecraft)
6. Telemetry Modes (Defines the rates at which we write to the SSR and downlink to Earth)
7. Mission Milestones and Key events such as Ring plane crossings or Titan Flybys
8. Segment and Sequence boundaries
9. Reaction Wheel Biases
10. Orbit Trim Maneuvers (OTMs)
11. Waypoint and Downlink Turns
12. Timeline graphic information for export
13. Identification of unique transitional or “custom” periods
14. “Deadtime” where activities are prohibited
15. Links to associated external files

Outside of requests, CIMS further maintains a wide assortment of information that is not tied to the requests. One such database revolves around specific liens on each delivery. The source of these liens is twofold. First, violations of the relationships between science and non-science requests are flagged with the option to promote the violation to a lien and second, science teams enter a lien manually often as a reminder for some unresolved issue. The information stored in the database of liens includes the type of lien against a particular time period, the team responsible for the resolution of the specified lien, the status, the proposed solutions to those liens, and the resolution of the lien if it has been corrected or a waiver has been submitted and approved.

IV. The CIMS function in Cassini Operations

As stated by Mishkin et al, the most essential element for distributed operations is “full access to planning and analysis tools, and data, at remote sites”. CIMS provides that access. Operationally, CIMS is the central hub for all science and engineering agreements made during the sequence development process and plays a pivotal role in the configuration management of those agreements.

Once a Tour is selected, it is divided into approximately 40-day sequences that are then broken into segments ranging in duration from 2 days during Titan flybys to 10 or more days for extended periods at apoapse. Teams then populate each segment with desired pointing, power, and data volume and then extensive negotiations take place to resolve the resource conflicts. Once the conflicts are resolved, there is one team per request who is responsible for the pointing design for that period of time. This is known as the “Prime” instrument. Because of the co-alignment of the ORS instruments, however, the other remote sensing teams can add “Rider” requests, which collect supplemental data in parallel with the Prime instrument. These “Rider” requests are important because they provide context and supplemental data of the same target that the Prime instrument is observing. The MAPS instruments also collect data during these Prime request periods. For example, the ISS instrument might be observing the surface of Titan, while the VIMS instrument gathers information regarding the chemical composition of various features and the INMS instrument collects data on the atmosphere of Titan simultaneously. Once agreements for who will be “Prime” and who will be the “Riders” are in place, teams log in remotely and either make manual edits to CIMS via a web browser or upload an XML file to CIMS to perform the same function.

After logging into the system, CIMS recognizes both the user that has logged in and the user’s team affiliation. Based on this identity, CIMS grants permissions to that user to modify only the requests of his or her team. This is critical to configuration management with distributed operations. An inadvertent modification to a request that does not belong to the user could cause a chain reaction of events and problems with the sequence. The change that is made as well as the name and team of the user who makes the change are also logged for tracking and configuration management purposes.

CIMS has been equipped to handle a suite of import and export options including XML, HTML, a tab-delimited file for import into Excel, and custom formats including an Activity Planning File (APF) and
Science Planning Attitude Strategy Spreadsheet (SPASS) that are used with external tools such as the SSR Management Tool (SMT) and a DSN and downlink rate verification tool.

The Science Planning Engineer who is managing the process will see these edits in CIMS come into the sequence as additions, modifications, and deletions through a notification system on the CIMS GUI. These requests can then be accepted as Pending, Approved, or Denied depending upon the situation and agreements that have been made previously in the process. This level of control is also an important layer in the Configuration Management strategy of CIMS. It ensures that teams can not make unilateral changes to the agreements in CIMS without proper approval. Once the changes have been incorporated, a CIMS utility known as the “Resource Checker” is enabled to look for violations of the rules imposed on each request as well as violations of the interdependent conditions, which are listed in a report to be evaluated by the Science Planning Engineer.

The Resource Checker utility is an enhancement to CIMS added over the course of the Prime Mission. The CIMS developers worked closely with the Science Planners to develop enhancements that aided operations, lowered cost, and made the final sequence product more robust. And through this customizable Resource Checker, fifty complex interrelationships between agreed upon data are checked. Some examples of what CIMS will report include:

1. Invalid naming conventions
2. Overlaps and Gaps between Prime Requests
3. Downlinks with inadequate DSN support
4. Conflicts with DSN maintenance
5. Conflicts with Primary and Secondary pointing
6. Conflicting telemetry mode changes
7. Conflicts between OTMs and downlinks

It is important to note that CIMS is for the most part a planning and resource allocation tool, and not a sequence generation tool. The sequence that is radiated to the spacecraft only in part comes from CIMS. Specifically, the downlinks, the turns to and from the downlinks, waypoint turns, data volume envelopes, and telemetry modes are generated via information in CIMS. CIMS does have the capability to generate a fully integrated sequence however, the distributed ops teams felt strongly that the team sequence products used in the merge of the final sequence should come from the distributed ops sites which are loaded into a file sharing site known as the Distributed Object Manager (DOM). The sequence product generation process and the CIMS modification process run in parallel. Working with the Science Planners, the CIMS developers incorporated a function to bridge these parallel processes. A new automated comparing process, called the “SPASS-SASF compare” was developed. For this comparison, the actual sequence products are directly ingested into CIMS and this information is correlated between the merged Spacecraft Activity Sequence File (SASF) and requests in CIMS. CIMS can perform this function in a matter of minutes where. Prior to this automated functionality, this process of comparing thousands of fields was done by hand, was prone to errors, and extremely time consuming. While this compare process in CIMS is not foolproof, it does identify significant and even subtle differences between the agreements in CIMS and the actual merged sequence file. This process also verifies the scientific intent of the sequence to ensure that it matches the science agreements captured in CIMS. Due to the cooperative nature of the science being collected, this last point is especially important. The change in one Prime observation can affect all of the Riders for that observation so there is careful coordination that is required for all changes to the Prime science being captured.

During Prime Mission, Cassini has also experienced some problems with retrieving full downlinks from the DSN. As a result of this, the operations teams agreed that “high value” science should be played back twice to give DSN stations two opportunities to collect this data set without losses. To aid with this operation, the functionality to compute the data volume associated with this “high value” science period to help with planning was developed in CIMS. This computation from CIMS is used to model the effect of this dual playback on the SSR on-board the spacecraft.
V. Conclusion

The Cassini mission is exceedingly complex for three central reasons, the diverse science, the spacecraft complexity, and distributed operations. The science objectives are diverse, often unique, and evolve over time as new discoveries are made. As a result of this, the sequence generation cycle is lengthy and there is an intense focus on science optimization making integration of science and engineering requests challenging. Additionally, the number instruments on-board Cassini (4 ORS and 8 MAPS instruments) requires a greater level of negotiation during sequence integration. For example, the number of requests is significantly higher, hand-off attitudes need to be specified, and the Riding instruments will levy requirements on the Prime observations. Distributed operations compounds the challenge due to time zone differences, configuration management issues, and visibility into present agreements on resource allocation.

CIMS addresses these complexities and bridges a critical gap in Cassini operations between the distributed ops teams and the sequencing process. It does this through facilitating the communications of all distributed ops sites, employing a centralized database containing science and engineering agreements that is easily accessible to anyone with permission to enter the site. This alone saves a significant amount of workforce hours as teams are not forced to gather and track information from multiple sources. And finally, CIMS lays the foundation for this distributed ops coordination through an extensive configuration management design that includes user tracking and restricted access for edits, approval of edits, and version control on all elements in CIMS.

While designed for Cassini, CIMS is still adaptable for other projects that have a wide assortment of requirements. It is a web-based tool that is accessible from distributed ops sites through any web browser and customizable via an interactive relational database. It is also a tool which helps guide the flow of the ops process, provides layers of configuration management on the sequence agreements, and allows for a suite of utilities that aid in the efficiency of timeline evaluation. As stated by Burket et al, “The infrastructure is applicable to any situation in which there is a need for all or a subset of the following features:

- Easy, yet secure, access to centralized data from a variety of locations and platforms
- Configuration management of evolving information
- Management of complex data relationships
- Management of complex procedures
- Multiple input and output formats to/from a centralized data repository
- Automatic user notifications for system events”

Looking to the future on Cassini, there were several additional functions that could potentially be implemented into CIMS. For example, CIMS currently exports a wide variety of files, those files are moved to a work station or PC, and other tools are invoked to perform various operations on those files including SSR modeling, downlink rate recomputation, and timeline generation and reformating. These functions performed by outside scripts could be incorporated into CIMS. Further, as we discussed, CIMS is not used to generate the final sequence products. This functionality, the generation of a merged and final sequence product based on the science agreements captured in CIMS, was also considered but not implemented.

With Cassini, CIMS provides these functionalities and enables distributed operations to proceed with less risk, at a lower cost, and in less time. Adaptability to another distributed operations mission would be a modest delta from the current configuration which has been optimized for Cassini Operations.

Acknowledgements

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References


Figure 2. Snapshot of the requests in CIMS delivery
Figure 3. Sample of a UVIS request in CIMS