The Cassini-Huygens Mission Overview

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The *Cassini-Huygens* Program is an international science mission to the Saturnian system. Three space agencies and seventeen nations contributed to building the *Cassini* spacecraft and *Huygens* probe. The *Cassini* orbiter is managed and operated by NASA's Jet Propulsion Laboratory. The *Huygens* probe was built and operated by the European Space Agency. The mission design for *Cassini-Huygens* calls for a four-year orbital survey of Saturn, its rings, magnetosphere, and satellites, and the descent into Titan's atmosphere of the *Huygens* probe. The *Cassini* orbiter tour consists of 76 orbits around Saturn with 45 close Titan flybys and 8 targeted icy satellite flybys. The *Cassini* orbiter spacecraft carries twelve scientific instruments that are performing a wide range of observations on a multitude of designated targets. The *Huygens* probe carried six additional instruments that provided *in-situ* sampling of the atmosphere and surface of Titan. The multi-national nature of this mission poses significant challenges in the area of flight operations. This paper will provide an overview of the mission, spacecraft, organization and flight operations environment used for the *Cassini-Huygens* Mission. It will address the operational complexities of the spacecraft and the science instruments and the approach used by *Cassini-Huygens* to address these issues.

I. The Mission

Saturn has fascinated observers for over 300 years. The only planet whose rings were visible from Earth with primitive telescopes, it was not until the age of robotic spacecraft that questions about the Saturnian system's composition could be answered. Previous robotic spacecraft encounters with Saturn were the flybys of Pioneer 11 in 1979, Voyager 1 in 1980, and Voyager 2 in 1981. Plans for a dedicated Saturn orbiter were begun in 1982 and became the Cassini-Huygens mission. Launched from Cape Canveral on October 15, 1997, the Cassini-Huygens spacecraft reached the Saturnian region in July 2004. After a seven-year, 2-billion mile voyage that included four gravity-assist planetary flybys, the Cassini orbiter entered Saturn's domain and began a four-year mission featuring 76 orbits around the ringed planet and its moons and deployment of the Huygens probe into Titan's atmosphere. The main scientific goals include measuring Saturn's huge magnetosphere, analyzing, from up close, the stunning ring system, studying Saturn's composition and atmosphere, as well as detailed, targeted observation campaigns of Titan and the other large satellites.

The design of the Cassini primary mission involved trades between competing objectives. Science objectives at Saturn include investigations into atmospheric properties and composition, internal structure and rotation, and the ionosphere. The rings of Saturn are being observed for structure and composition, dynamical processes, interrelation between the rings and satellites, and the dust/micrometeoroid environment. The magnetosphere of Saturn is to be investigated for its dynamical configuration, particle composition, sources, and interactions with the solar wind, satellites, and the rings. The icy satellites will be examined for their characteristics, geological histories, mechanisms of surface modification, and internal structure. Titan, the second-largest satellite in the solar system and most Earth-like, will be closely examined for its atmospheric composition, winds and temperatures, and surface state and composition.

Obtaining these diverse objectives in a four year time span was a challenge. A purely equatorial tour, while best for conserving propellant (and thus enabling a possible extended mission), missed in-situ sampling of the whole of the magnetosphere, as well as being ineffective for ring observations, as the rings are only 30 meters thick at most. Multiple consecutive short-duration orbits were not feasible from an operations standpoint. Close targeted flybys of many of the major and minor satellites were also desired. A targeted flyby is one where the orbiter's trajectory has been designed to pass through a specified aimpoint (latitude, longitude, and altitude) at closest approach. However, multiple close Titan encounters were necessary to rotate the orbit out of the ring plane, as only Titan is massive enough to use for orbit control. A single flyby can change Cassini's Saturn-relative velocity by more than 800 meters per second. The other satellites can only change Cassini's trajectory slightly, even for close flybys. Therefore, there are many Titan flybys, and each must be designed to return the spacecraft to Titan to remain on tour.

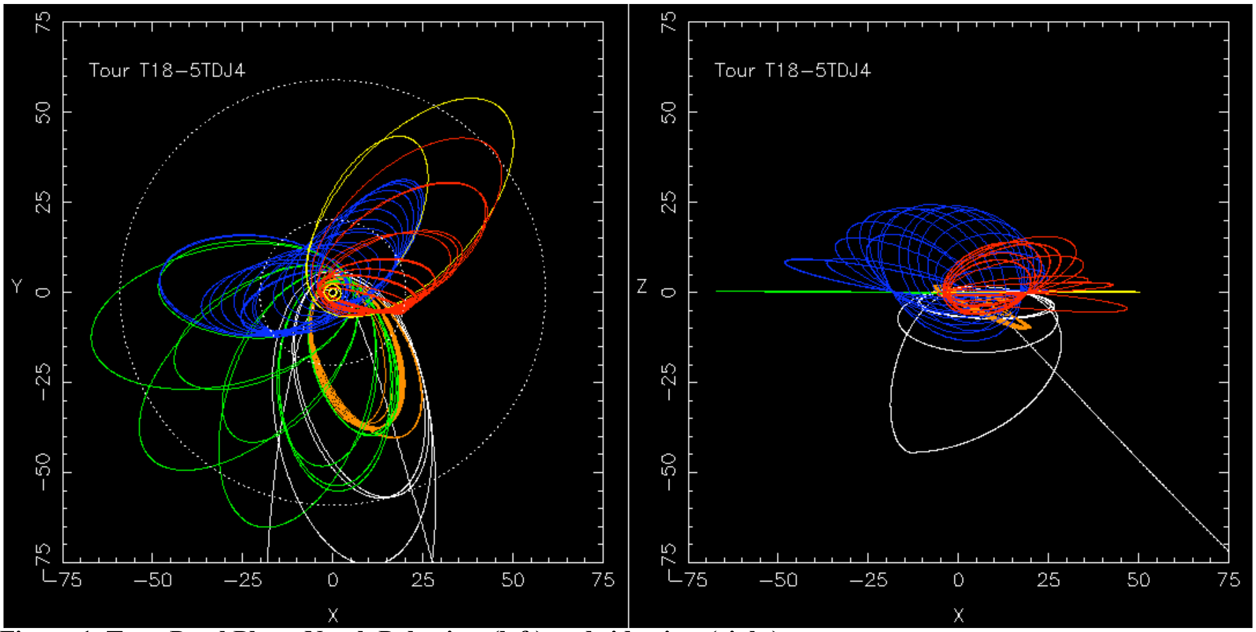

Figure 1. Tour Petal Plot – North Pole view (left) and side view (right)

The plot in Figure 1 is known as a "petal" plot, which shows how targeted flybys combine with orbit drift to rotate the orbital properties. The four-year primary mission consists of 45 close Titan flybys and 8 targeted icy satellite flybys – Phoebe, Enceladus (3), Hyperion, Dione, Rhea, and Iapetus. There are also numerous encounters with these and other icy satellites that are not targeted – i.e., the spacecraft trajectory is not specifically controlled to maintain a planned flyby timing and geometry. The spacecraft's planned position relative to Saturn and its satellites at any time is known as the "reference trajectory". This was used extensively in planning observations several years ahead of time, and any changes to the reference trajectory can cause a large amount of rework.

II. The Spacecraft and Instruments

Cassini is a three-axis stabilized spacecraft outfitted with 12 diverse science investigations (Figure 2). The instruments often have multiple functions, equipped to thoroughly investigate all the important elements of the Saturnian system. Cassini's remote sensing instruments provide data for global studies of Saturn's atmospheric temperatures, clouds, and composition, as well as studies of Saturn's rings and its many natural satellites. Each instrument will provide unique types of data to help solve the puzzles of Saturn. The Composite Infrared Spectrometer (CIRS) provides the temperature and composition of surfaces, atmospheres, and the rings. The other two spectrometers on Cassini are the Ultraviolet Imaging Spectrograph (UVIS) and the Visible and Infrared Mapping Spectrometer (VIMS). These three instruments complement each other in measurements of atmospheric composition, measuring chemical and/or atomic composition at multiple wavelengths. The Imaging Science Subsystem (ISS) utilizes both a wide angle and narrow angle camera to perform multispectral imaging of the planet, its major and minor satellites, and rings.

The Cassini RADAR provides microwave radar imaging, altimetry, and passive radiometry of Saturn and its satellites. The RADAR can see through Titan's murky atmosphere and is producing maps of Titan's surface and measuring the height of surface objects such as mountains and canyons.

Radio Science (RSS) experiments use the spacecraft's radio and ground-based antennas as the science instrument. Cassini sends microwave radio signals through the atmosphere of Saturn or Titan, which alters the signal. RSS data can be used to measure atmospheric and ring structure, as well as gravity fields and gravitational waves.

As opposed to remote sensing, the other 6 Cassini instruments are considered in-situ investigations collectively known as the Magnetospheric and Plasma Science (MAPS) instruments. The Cassini Plasma Spectrometer (CAPS) studies plasma within and near Saturn's magnetic field. The Cosmic Dust Analyzer (CDA) studies ice and dust grains in the Saturnian system, as well as on the journey there. The Ion and Neutral Mass Spectrometer (INMS) measures the in-situ composition of neutral and charged particles. The magnetometer (MAG) has an inboard and outboard sensor to measure the strength and direction of the magnetic field throughout the magnetosphere. The first-ever images of Saturn's hot plasma regions will be obtained by the Magnetospheric Imaging Instrument (MIMI), which also performs in-situ measurements of ions and electrons. The Radio and Plasma Wave Science (RPWS) instrument detects radiation and plasma wave emissions.

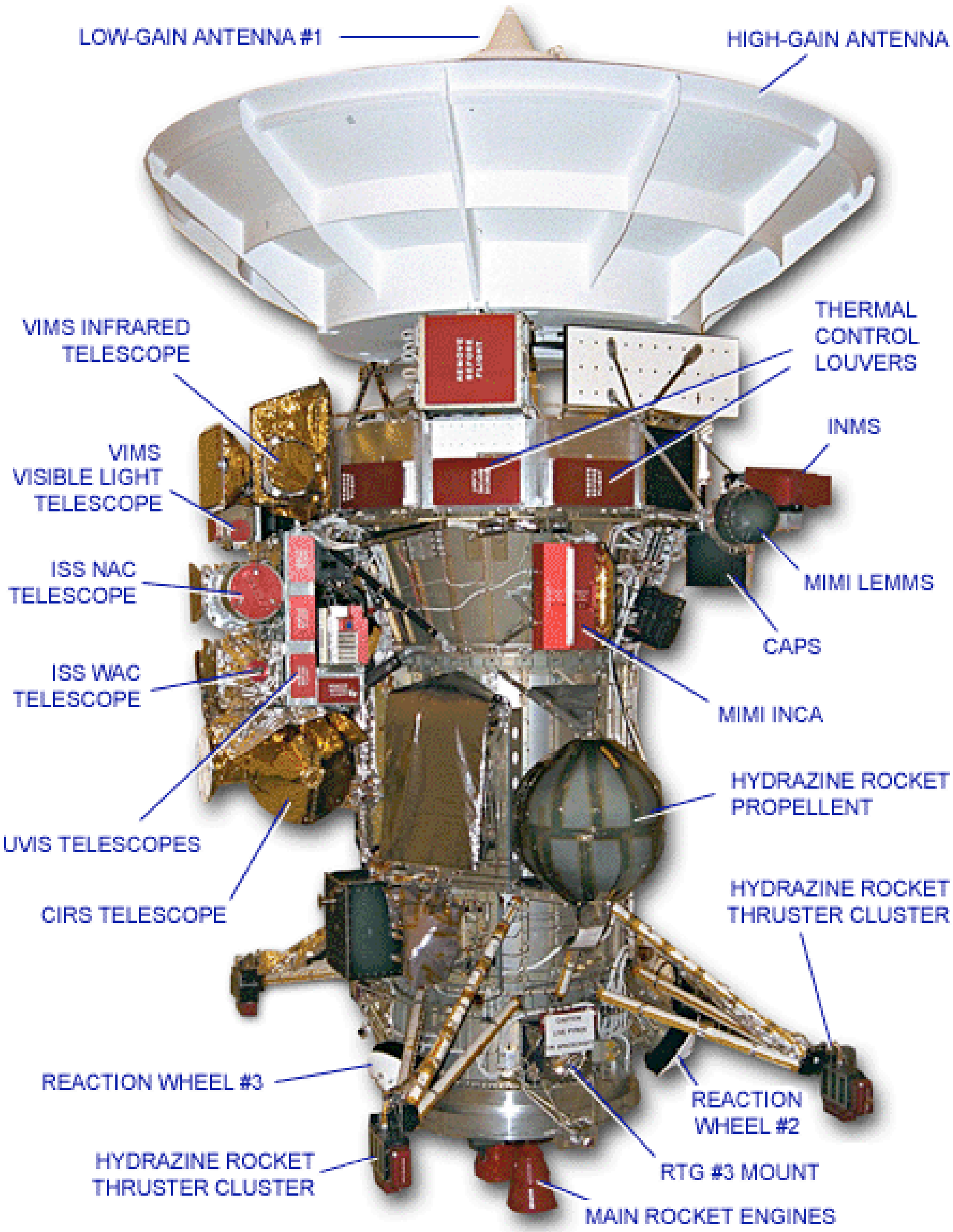

Figure 2. Cassini Spacecraft

The Huygens probe carried its own complement of 6 science instruments. They performed in-situ measurements of Titan's atmosphere and its surface, and are described in a separate paper.

The spacecraft communicates through one high-gain and two low-gain antennas. Power is provided by three Radioisotope Thermoelectric Generators (RTGs). The Attitude and Articulation Control Subsystem (AACS) uses three Inertial Reference Units (IRUSs) and a Stellar Reference Unit (SRU), or star tracker, to determine both the spacecraft's position and orientation. Reaction Wheel Assemblies (RWAs) are one of the two systems used to provide pointing control of the spacecraft in flight (with the thrusters of the Propulsion Module Subsystem as the other). The thrusters, along with a main engine, also perform orbit trim maneuvers (OTM's) to keep Cassini following the chosen trajectory around Saturn.

The science instruments are all body-mounted; a scan platform was deleted as a cost-saving measure during spacecraft design and integration. Thus the entire spacecraft must be rotated for any one instrument to achieve a desired pointing attitude, and also to point the high gain antenna at Earth for communications. Data taken by the instruments is stored on two solid-state recorders (SSR), with a capacity of 4 gigabits. The spacecraft utilizes the Deep Space Network to downlink, on average, over one gigabit of data daily.

III. Cassini Operations Planning

On a typical day in the Cassini tour, the spacecraft collects science data for 15 hours by orienting the spacecraft at a variety of targets. One instrument at a time controls the pointing of the spacecraft, and other instruments may "ride along" and collect data at the same time. The remaining 9 hours is spent in one block on Earth-point, downlinking the data. During the downlink, MAPS instruments continue to collect science data- often the spacecraft is rolled around the earth-pointed attitude to facilitate this data collection. Control of the spacecraft is done, for the most part, from autonomous sequences stored onboard the spacecraft. Spacecraft sequencing uses a combination of centralized commands (for control of the system level resources) and instrument commands to conduct activities and maintain the health and safety of the spacecraft. The spacecraft is flown with sufficient margins to allow the instruments to operate fairly independently from each other, and with a minimum of real-time ground intervention.

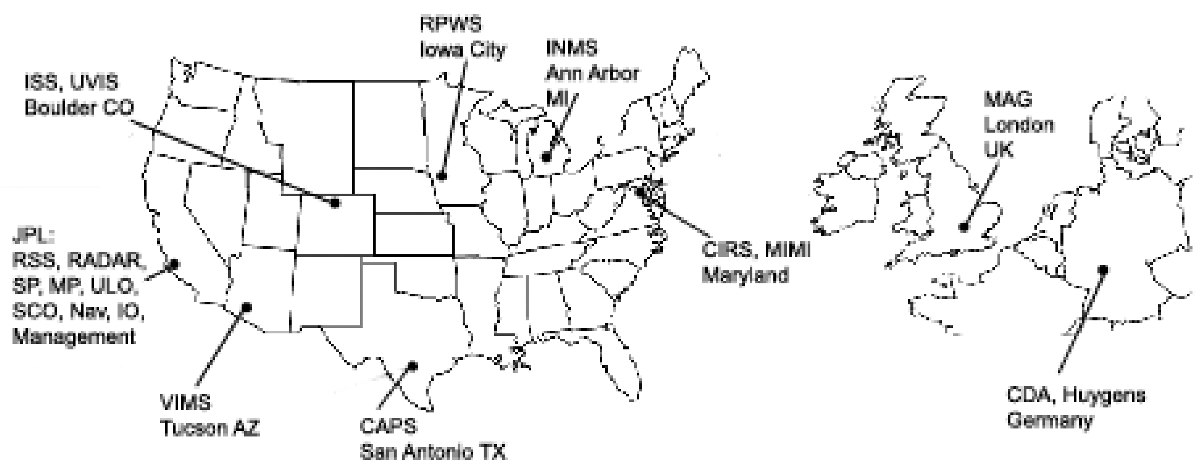

Figure 3. Cassini Operations

The operation of the Cassini spacecraft is centered at the Jet Propulsion Laboratory (JPL) in Pasadena, California. The Huygens Titan Probe was operated from the Huygens Probe Operations Centre in Darmstadt, Germany. The Cassini mission planning, real-time operations, science planning/sequence integration, navigation, and spacecraft operations teams, as well as the program management, are co-located at JPL. The science teams are led using a distributed operations structure to allow scientists to operate their instruments from their home institutions, which are spread across different states and even different countries (Figure 3). Cassini instruments that serve multiple investigations are called facility instruments. Facility instruments were provided by JPL, the NASA Goddard Space Flight Center or by ASI. A JPL team called the instrument operations team (IO) operates the facility instruments, except for INMS. Instruments that serve individual investigations are provided and operated by a

Principal Investigator (the INMS is operated like a Principal Investigator instrument). Figure 3 shows the distribution of instrument operations. For teams not resident at JPL, an Investigation Scientist or dedicated member of the Instrument Operations team assists in timely production and review of sequence products.

Distributed operations places observing decisions, including generation of instrument internal subsequences, in the hands of the science teams. The implementation of distributed operations for the Cassini mission is achieved through computers, computer-resident software and communication lines provided by JPL to the remote sites, as well as science participation in the uplink (mission planning, sequence development) and downlink (Principal Investigator instrument health monitoring) processes. Cassini uses virtual teams for mission planning and sequence development. These teams bring together people for the development of a given product. Their membership varies, depending on the particular subphase or sequence to be developed. Each virtual team member maintains membership in his/her mission team of origin and continues to work for that team while providing expertise to and generating products for the virtual team.

The Mission Planning Team leads the effort to design the tour and periodically update the reference trajectory. This effort is focused on maximizing the science opportunities of the mission. It is during the Mission Planning phase where decisions are made regarding how many orbits, how many Titan flybys, which icy satellites will be targeted - how often and at what orientation. The initial tour design for Cassini took place over 6 years. The science community played an integral role in this process.

The Science Planning Process follows tour design. First is the creation of the Tour Atlas, which identifies the specific science opportunities in the selected tour. The detailed information (phase, altitude, surface ground track, etc.) for each targeted flyby is provided.

Next, development of the Science Operations Plan (SOP) is broken down into two major phases: Integration and Implementation. Integration is the process by which the science and engineering teams negotiate the basic pointing, power, and data management strategy. Implementation is the process by which these plans are validated. This step has already been completed for the entire 4 year prime mission, meaning some sequences will “sit on the shelf” for several years before the next step.

The details of Integration and Implementation are critical to the overall process of Cassini Science Planning. Science Planning leads discipline-focused groups to share the responsibly and the workload of integrating the Tour. These groups are Rings, Atmospheres, Icy Satellites, Titan, Magnetosphere, and Cross-Discipline. The four-year tour was subdivided into roughly 200 smaller time segments based on science discipline. Integrating the Tour based on this segmentation leads to a more science-optimized plan. The process has matured significantly over the past several years.

The output of Integration is a conflict-free timeline of all science observations and engineering activities stored in a centralized database. These activities have associated data volumes that are consistent with the downlink strategy (also incorporated into the timeline). Specific Deep Space Network (DSN) station requests are made for each sequence. The integrated plan also identifies the instruments responsible for controlling the attitude of the spacecraft as a function of time.

During Implementation, the Science Instrument Teams, Science Planning, Optical Navigation, and the Spacecraft Operations Team (SCO) generate the detailed spacecraft pointing and data acquisition commands necessary to accomplish the integrated science plan. An end-to-end pointing profile validation is conducted during Implementation. All teams, in particular the spacecraft team, validate the final merged sequence.

The Aftermarket and SOP Update processes are used to update the SOP while in tour with the latest information on spacecraft performance, science opportunities, and ephemerides. The Aftermarket process is where the effects of a new reference trajectory, changed science priorities, and/or changed downlink times are integrated into the plan. The SOP Update process is where this updated plan is re-implemented and re-validated.

Following SOP update, the uplink operations team (ULO) takes over the lead role for the Science and Sequencing Update Process (SSUP). Two more validation cycles are performed, with increasing limitations on the types of changes allowed. There is no more science optimization, and spacecraft health and safety are the main goals. Unique or first-time events are simulated on a testbed prior to the sequence being uplinked to the spacecraft.

The overall timeline of events associated with the Cassini uplink development process is given in Table 1. This chart maps out the timeframe for the key steps in the uplink process, the key players, and the goal of each step. It covers the time period from Tour Design to the sequencing process that occurs just prior to radiation of the sequence command load to the spacecraft.

When	What (goals)	Who	Details
10 years before Prime Mission	**Tour Design** (maximize science opportunity)	Science Community, Mission Planning, Navigation (some SCO)	Science experiment trade-offs, navigation and uplink development capabilities.
4 years before PM	**Integration** (negotiate best science compromise)	Science Planning, Science Community (some SCO, some Mission Planning)	Break up entire mission by science discipline and negotiate shared resources (pointing, power, telemetry, and data volume); lack of a scan platform makes this a challenge.
2 years before PM	**SOP (Implementation)** (validate basic sequence design)	Science Planning, Science Community, SCO (some Mission Planning)	2 validation cycles to get a 'flyable' skeleton sequence of the shared resources in place; distributed operations makes this a challenge.
20 weeks before execution	**Aftermarket (Adaptation)** (update integrated plan)	Science Planning, Science Community (some SCO, some Mission Planning)	Update integrated plan based on new discoveries, science data analysis, spacecraft/instrument performance changes, etc.
15 weeks before execution	**SOP Update** (update basic sequence design)	Science Planning, Science Community, SCO (some Mission Planning)	A validation cycle to update the skeleton sequence to any updated science compromises and/or new discoveries.
10 weeks before execution	**SSUP** (validate entire sequence)	ULO Sequence Lead, Science Community, SCO (some Science Planning)	2 validation cycles to create a complete sequence with all commands in place; complexity of spacecraft and plans make this a challenge.

Table 1. Cassini Uplink Development Timeline

IV. Lessons from the First Two Years

A. Reference Trajectory Updates

The primary mission reference trajectory used for the first sequence was released in 2003. Several modifications, or "tweaks", have been necessary since (Table 2). The reference trajectory was always planned to be updated reflecting the knowledge gained on approach from optical navigation and radio tracking. However, the initial release in May 2004 incorporating this knowledge did not take into account the amount of on-the-shelf sequence integration that would need to be redone if there were no constraints placed on the new trajectory relative to the previous one. While propellant margin at the end of prime mission was a concern (due to limiting the length of any extended mission), the personnel were simply not available to perform the rework unless science data was sacrificed. It was decided to spend some propellant to introduce constraints on any new reference trajectories. A process was developed for science team input and collaboration with mission planning and navigation to minimize science impacts.

The next reason for a reference trajectory update (in October 2004) was to protect the Huygens probe mission. After release, the probe was on a ballistic trajectory to Titan. The probe was due to pass within 57,000 km of Iapetus a week after release, and two weeks before Titan arrival. After orbit insertion, the inclusion of radiometric data caused the estimate of Iapetus' mass to move around more than would have been expected based on the statistical uncertainties in prior estimates. The effects of any errors in the value used for the mass of Iapetus would map directly into errors in the probe entry flight path angle. Various options were explored to mitigate this concern, and ultimately the trajectory was tweaked so that the probe passed over 100,000 km from Iapetus.

Reference trajectory release date (YYMMDD)	Sequences using it	Why updated
030201	S01	Initial prime mission tour
040506	-	Incorporated knowledge gained on approach to Saturn
040513	S02-S03	Fixed error in 040506 release
040622	S04	Tweaks to 040513 to minimize sequence reintegration required
041001	S05-S07	Increase the distance between released probe and Iapetus
041210	S08-S11	Two upcoming 950 km Titan flybys (T5,T7) raised to 1025 km
050505	S12	3 upcoming icy satellite flybys improved (closer)
050720	S13-S19	T7 1025 km Titan flyby re-raised to 1075 km
060323	S20-current	Remaining 950 km Titan flybys tweaked (mostly higher)

Table 2. Reference Trajectory Updates

Analysis of Titan atmosphere density data over the first several Titan flybys raised concern of the spacecraft tumbling at a flyby altitude previously thought safe. Originally there were 23 Titan flybys at 950 km altitude, with two in 2005 and the rest after mid-2006. The Titan Atmospheric Working Group (TAMWG) analyzed data from the INMS instrument, UVIS stellar occultation, and AACS performance during the first 3 Titan passes under 2000 km to estimate an initial safe altitude of 1025 km for the next two flybys (T5 and T7), which was implemented in December 2004.

The navigation team, investigating trajectory variations, found a way to greatly improve three icy satellite flybys at nearly no propellant cost. This was implemented in May 2005 and lowered a targeted Enceladus flyby from 1000 km to 175 km, a non-targeted Tethys flyby from 29,770 km to 1500 km, and our only targeted Hyperion flyby from 1000 km to 500 km. Images from those flybys are found in Figures 4 and 6.

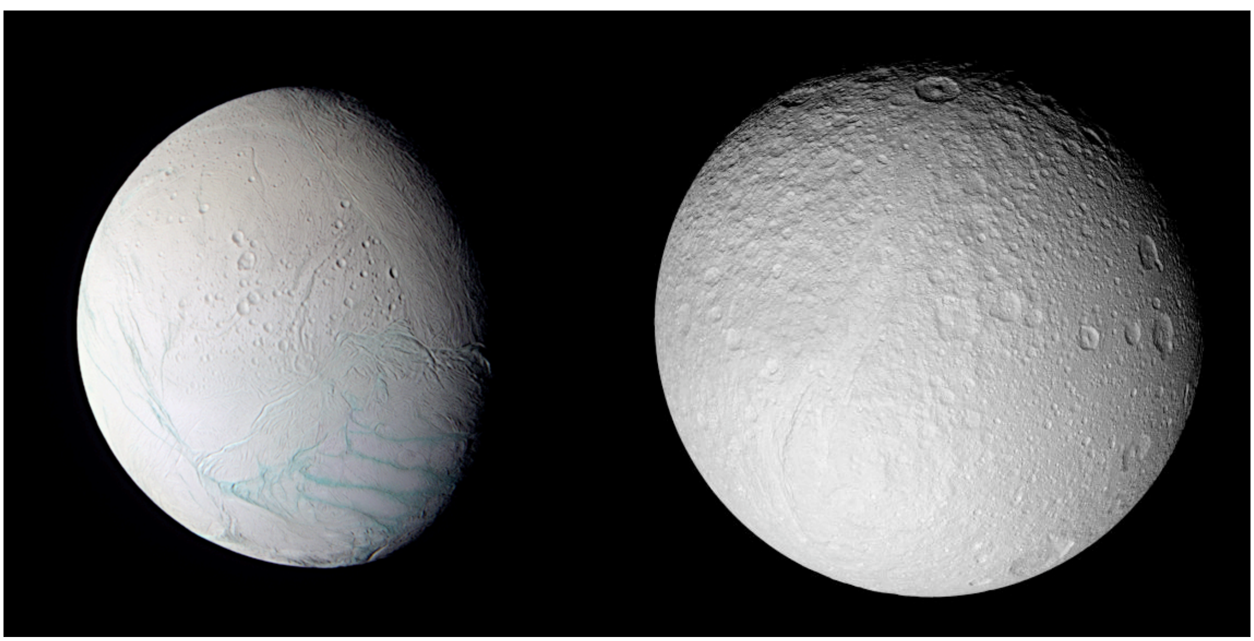

Figure 4. Enceladus (left), Tethys (right)

Further analysis using data from the 1025 km T5 flyby and some Huygens data raised enough concern in the TAMWG to re-raise the T7 attitude to 1075 km in a July 2005 trajectory delivery.

Data from all the Titan passes led to the most recent trajectory update in March 2006, in which all remaining 950 km flybys were adjusted. The orientation of the spacecraft and the latitude of Titan closest approach were both factored in; some flybys were raised to over 1000 km, while two could remain at 950 km. The navigation team worked closely with the science community to both improve some icy satellite flybys while minimizing the effect on highly sensitive RSS occultation studies.

At least one further reference trajectory update is expected during the remaining 2.5 years of prime mission. Once an extended mission has been officially funded, the last few OTM's and final Titan flyby in the prime mission will need to be tweaked to match up with the plan for an extended mission tour trajectory. Mission planning, the science teams, and navigation are already working together to maximize science opportunities in an extended mission tour given the expected propellant remaining at the end of prime mission.

B. Live Updates

During execution of the sequence on the spacecraft, updated spacecraft position files become available at the time each OTM is performed. These OTM ephemeris files can then be used to update the pointing vectors onboard the spacecraft. This is known as a "live update". Prior to Prime Mission an analysis was done to estimate the number of live updates required. A Live Update Working Group was convened to refine these estimates, define and test the procedure for live updates, and work with navigation and the sequence leads to fit them in the busy schedule of other real-time commanding. Science planners use software developed in-house to analyze an OTM ephemeris to assess the necessity of a live update. Visualization tools show whether a body will be clipped, or missed entirely. The different instruments fields-of-view are also modelled. Workforce constraints are taken into account when planning a live update, as these generally are needed in the high-activity period surrounding a targeted flyby. As of May 1, sixteen live update products have been uplinked to the spacecraft, often containing updates for more than one target body. An additional 13 live update processes were cancelled as unnecessary. Only twice have live updates been missed – target bodies were clipped that would not have been had a live update been performed. These both occurred in early 2005. Since then, each new ephemeris is analyzed even if no live update is expected from the preplanning effort.

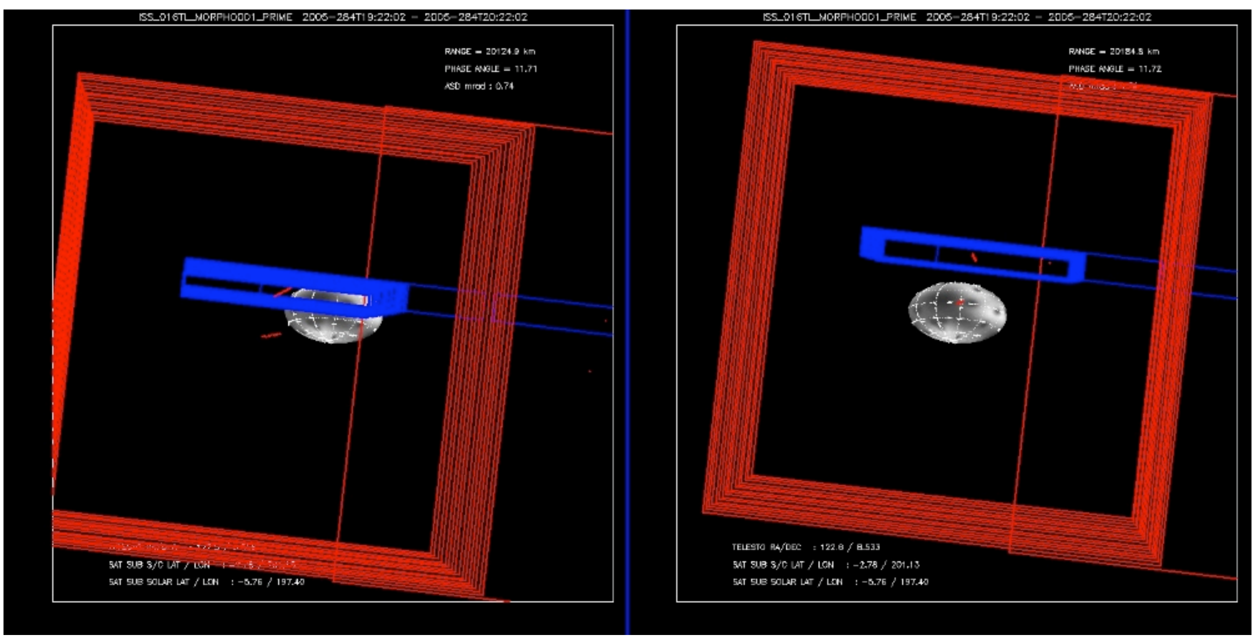

Figure 5. Analyzing necessity of live updates. *(left) planned pointing, (right) without update. CIRS instrument field-of-view (blue rectangles) misses target body (Telesto). Red squares are ISS narrow-angle field-of-view.*

Some observations are so sensitive to trajectory errors that they are built into a "live moveable block" (LMB) in which the timing of the observation can be shifted as well as the pointing. To date, seven LMB's have been performed.

During 2005 RSS discovered that some of their atmospheric occultation experiments needed to be done as a live movable block, without having been implemented that way. Without the groundwork from the live update working group, the spacecraft and uplink teams would not have felt comfortable with these late changes.

Sometimes, a planned OTM is not necessary – the spacecraft can be close enough to the reference trajectory from a navigation standpoint. In these cases, an analysis is made of the effect on science observations if the OTM is not performed. A live update can result in pointing as accurate as if the OTM had been performed. New procedures and software were developed in 2005 to incorporate this science planning analysis.

Figure 6. Results of live updates – Hyperion (left), Telesto (right)

V. Conclusions

The complexity of both the Cassini spacecraft and the distributed operations environment has required a large amount of advance science planning and sequencing to ensure safe, science-rich command products are ready on time.

The major driver of changes to the preliminary plans for each sequence has been a series of new reference trajectories. If developed from purely a navigation standpoint (minimizing propellant usage and ensuring spacecraft safety), much of the preliminary planning necessary to implement the 4-year Cassini prime mission science activities could have been largely wasted. When sequences have been integrated down to the minute, shifts in flyby timing of only a few minutes can require large amounts of rework. Also, Cassini negotiated with the Deep Space Network to provide our requested DSN station coverage over 20 weeks before execution. With the downlink times set in advance, there is less flexibility in science replanning and reoptimization.

Live updates, and the software developed to analyze the need for them, are critical to obtaining the best possible remote science observations. The software has matured significantly in the past year as new needs have risen, such as analyzing an OTM cancellation.

VI. Acknowledgement

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