Skirting Saturn's Rings and Skimming its Cloud Tops: Planning Cassini's End of Mission

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In October 2010, the Cassini spacecraft embarked on the seven-year Solstice Mission. The mission will culminate with a spectacular series of orbits that bring Cassini between Saturn's innermost ring, the D ring, and the cloud tops of the planet. The spacecraft will make its closest passages ever to the planet allowing for unprecedented science to be collected on Saturn and its rings. These final orbits will expose the spacecraft to new environments, which presents a number of challenges to planning the final mission phase. While these challenges will require adaptations to planning processes and operations, they are not insurmountable. This paper describes the challenges identified and the steps taken to mitigate them to enable collection of unique Saturn system science.

Nomenclature

CAPS	=	Cassini Plasma Spectrometer
CDA	=	Cosmic Dust Analyzer
CEM	=	Cassini Equinox Mission
CIRS	=	Composite Infrared Spectrometer
CSM	=	Cassini Solstice Mission
DWG	=	Discipline Working Group
HGA	=	High Gain Antenna
INMS	=	Ion and Neutral Mass Spectrometer
IVP	=	Inertial Vector Propagator Tool
ISS	=	Imaging Science Subsystem
KPT	=	Kinematic Predictor Tool
MAG	=	Magnetometer
MAPS	=	Magnetosphere and Plasma Science
ORS	=	Optical Remote Sensing
PIE	=	Pre-Integrated Event
PDT	=	Pointing Design Tool
PM	=	Prime Mission
R_S	=	Saturn Radii
RPWS	=	Radio and Plasma Wave Spectrometer
RSS	=	Radio Science Subsystem
TMC	=	Target Motion Compensation
UVIS	=	Ultraviolet Imaging Spectrometer
VIMS	=	Visible and Infrared Mapping Spectrometer

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I. Introduction

THE Cassini spacecraft has been exploring the Saturn system since its orbit insertion in July 2004. Upon successful completion of the prime (PM) and Cassini Equinox missions (CEM), the spacecraft began the Cassini Solstice mission (CSM) in October 2010. The CSM is a seven-year mission that ends in September 2017 when the spacecraft will impact Saturn. Prior to impact, the spacecraft will make 22 close passages to Saturn, flying in a ~2,200 km gap between the planet's innermost ring and its cloud tops. During these final orbits, Cassini's science instruments will gather data that will allow scientists to accurately determine the moments of Saturn's magnetic and gravitational fields at higher degrees than ever before possible, to refine knowledge of Saturn's internal structure and rotation rate, and better constrain the mass and age of Saturn's rings. However, the orbits will also expose the spacecraft to a new region of the Saturn system that the Cassini project never anticipated encountering, which presents a number of challenges to planning this final mission phase. Environmental hazards, such as impacts from tiny ring dust particles and drag from Saturn's atmosphere, define the gap the spacecraft can safely traverse and also limit spacecraft attitudes in order to protect sensitive spacecraft components. The close ranges to Saturn and the high velocities during the passages pose practical problems for obtaining certain science observations, limiting, for instance, the spacecraft's ability to track targets near periapse. But, these challenges can be managed and science objectives can still be achieved. The Cassini project's first step in planning for the final orbits has been to identify the challenges, characterize them, and determine how to mitigate them.

II. Proximal Orbits

The final 22 orbits of the CSM are named the proximal orbits because Cassini will pass closer than ever before to Saturn. The proximal orbit geometry is achieved by moving the spacecraft into highly inclined, short period orbits with a periapse just outside Saturn's main rings (the F Ring orbits in Fig. 1). A carefully designed single flyby of Titan (Saturn's largest moon) is then used to alter the spacecraft's trajectory such that it "hops" over the entire main ring system and places periapse inside the D ring[1] (see Fig. 2). Each proximal orbit has a period of 6.5 days and an inclination of ~62°. Periapse distances reach a minimum of 1.03 Saturn radii (R_S)[*] from the planet's center and relative velocities reach 34 km/s during closest approach. The high velocity of the spacecraft means the periapse passage happens quickly with the spacecraft traversing from Saturn-centered latitudes of 60°N to 60°S in roughly 2.5 hours. While the closest approach velocities will be greater than any previously experienced, the spacecraft's velocity falls off quickly away from Saturn and reaches typical levels about three hours from closest approach. Periapse occurs below the ring plane at latitudes of 5°S - 7°S. The periapse of the orbits was placed on Saturn's dayside, near noon local time, in order to satisfy specific science objectives. The inclination for these orbits was chosen to keep periapse on Saturn's dayside for all 22 orbits and to keep the spacecraft on a return path to Titan, which is used throughout the proximal orbits to shape the spacecraft's trajectory; away from this critical inclination apsidal rotation would occur due to Saturn's oblateness. The trajectory is also ballistic, meaning no maneuvers are required to guarantee final entry into Saturn's atmosphere once the proximal orbits begin.

The gap between the inner edge of Saturn's innermost ring, the D ring, and Saturn's upper atmosphere is ~2,200 km and it is believed to be safe for the spacecraft to traverse. The upper edge of the gap is limited by the inner periphery of the D ring, which may contain dust particles that can damage the spacecraft, while the lower edge of the gap is constrained by the atmosphere, which can cause the spacecraft to lose attitude control authority. The 22 proximal orbits cross through the gap at varying altitudes[†], ranging from 1622 km to 3407 km, which allows science measurements at different ranges within the gap (see Fig. 3).

The planned end of mission is to dispose of the spacecraft by impacting Saturn on 15 September 2017, in accordance with planetary protection requirements. After the 22nd proximal orbit, a final, distant flyby of Titan will bend the spacecraft's path such that it is on an impact trajectory with the planet. Since the proximal orbits trajectory is ballistic, impact with Saturn is assured regardless of the operability of the spacecraft during this time period[2].

[*] Distance from Saturn center divided by Saturn's radius

[†] Altitudes measured above Saturn's 1-bar shape

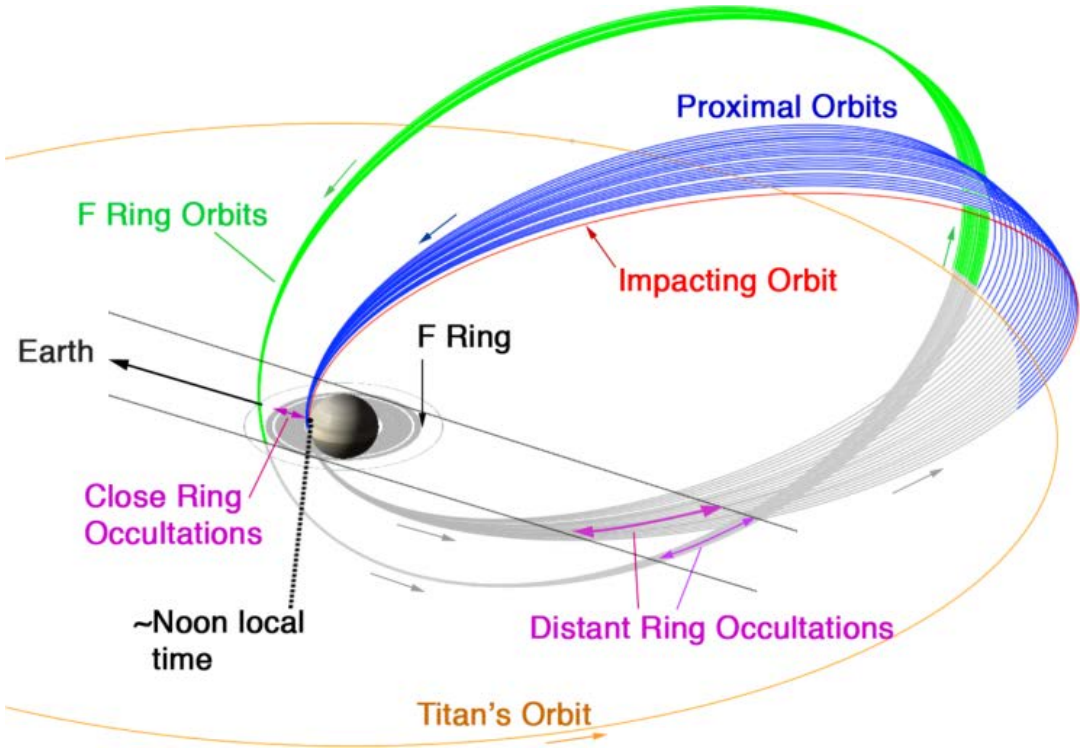

Figure 1. Proximal Orbits Trajectory.

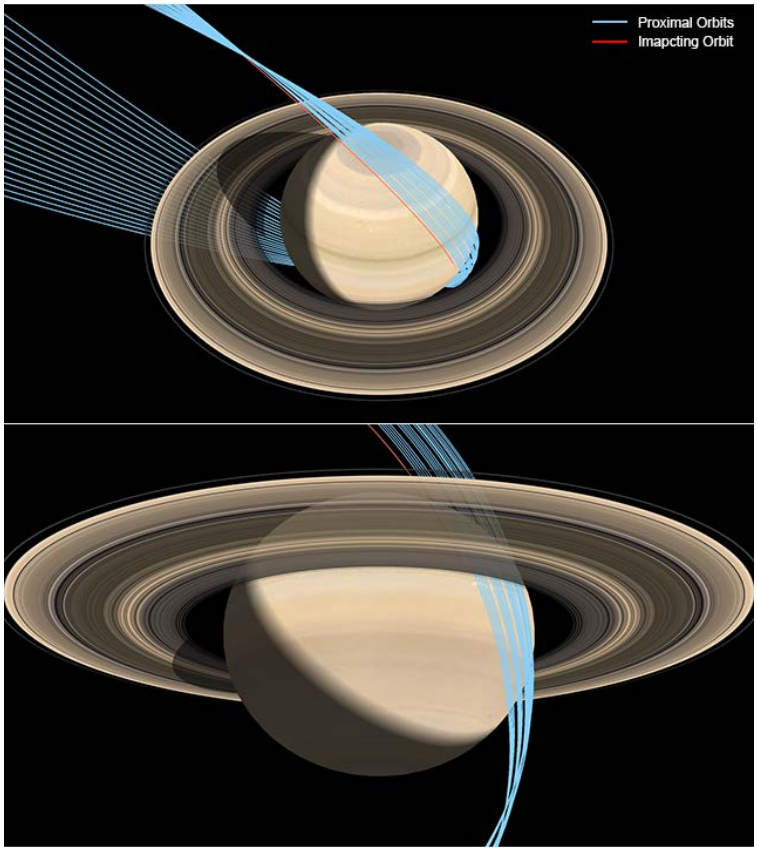

Figure 2. Proximal Orbits Periapse Crossings.

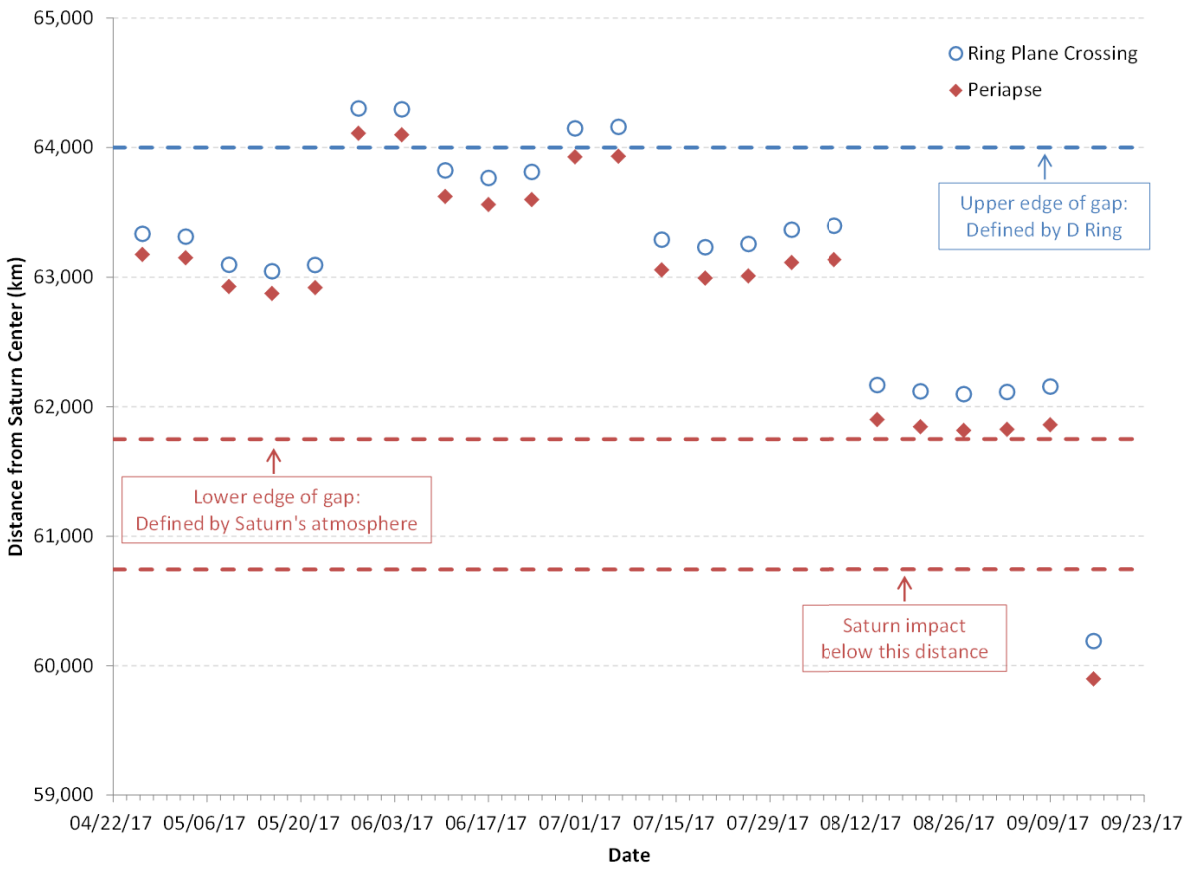

Figure 3. Proximal Orbits Crossings through Gap.

III. Cassini Spacecraft

The Cassini spacecraft, Fig. 4, is three-axis stabilized and measures 6.8 m tall with a maximum width of 4 m. The payload consists of 12 instruments which are divided into three categories: optical remote sensing (ORS), magnetosphere and plasma science (MAPS), and microwave remote sensing using the High Gain Antenna (HGA). Refer to Table 1 for a description of all instruments. The HGA also provides telecommunications. The HGA and all instruments are body-fixed to the spacecraft, meaning they cannot be pointed independently with respect to each other (with a few minor exceptions). Three radioisotope thermoelectric generators provide power to the spacecraft. Bipropellant main engines are used for large propulsive maneuvers, and monopropellant reaction control thrusters are used for small maneuvers and attitude control. Attitude control can also be provided by the reaction wheels.

At the start of the proximal orbits, the Cassini spacecraft will have been in flight for over 19 years. To date, overall health of the spacecraft and instruments is excellent. However, some hardware degradation has been experienced. The spacecraft is currently using the backup reaction wheel and the backup reaction control thruster branch. The Cassini Plasma Spectrometer instrument was turned off in 2012 after exhibiting anomalous electrical power behavior. The ultra-stable oscillator used during Radio Science Subsystem (RSS) occultation experiments failed in 2011; occultations can still be performed, though the accuracy of the data is degraded. Other types of RSS experiments are not impacted by this failure.

The spacecraft and instruments are expected to continue to perform well throughout the remainder of the CSM. Spacecraft operations engineers continue to track spacecraft performance and consumables are closely managed. Spacecraft power has been assessed and deemed adequate to conduct critical science observations through the end of mission. Also, sufficient propellant is projected to be available for proximal orbit operations.

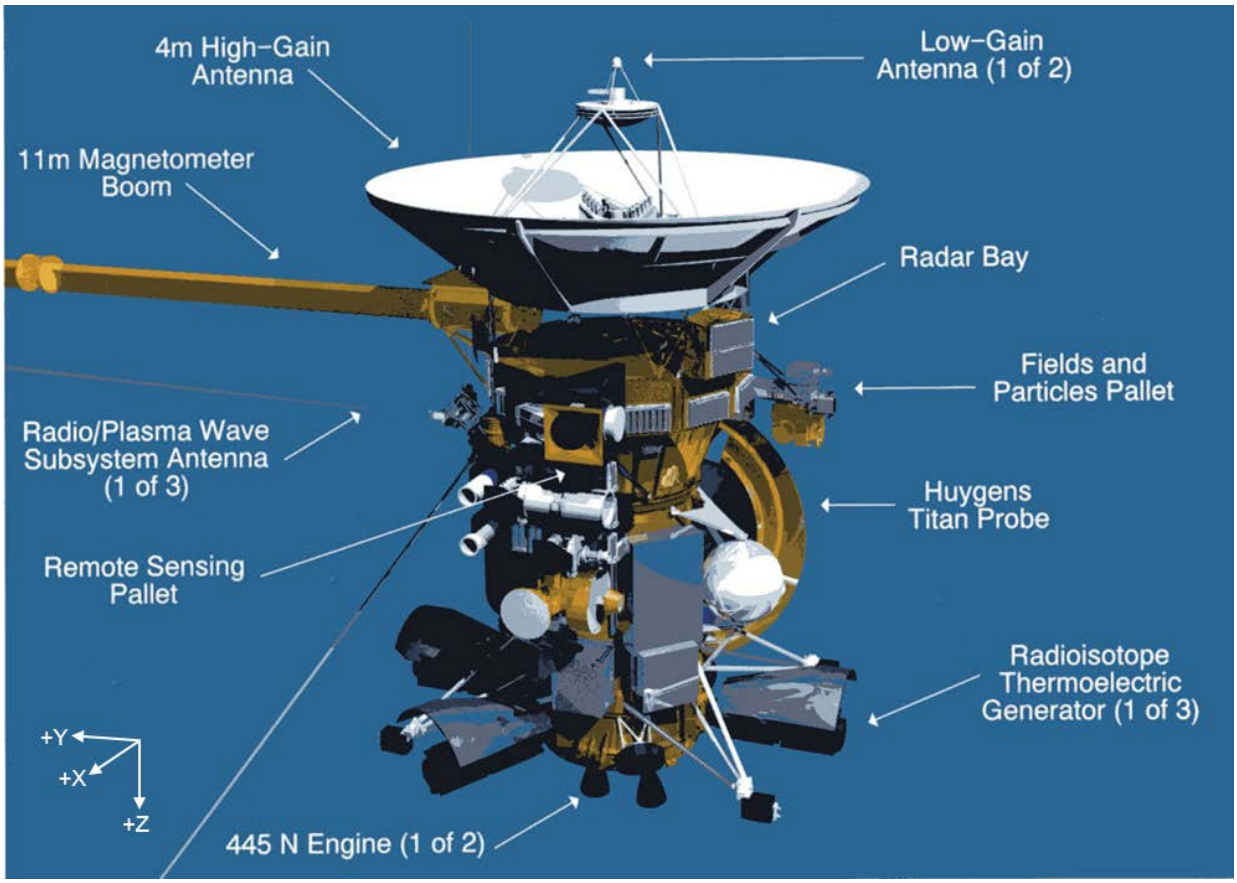

Figure 4. Cassini Spacecraft.

ORS	Composite Infrared Spectrometer (CIRS)	Measures infrared emissions to determine thermal properties and compositions
	Imaging Science Subsytem (ISS)	Narrow- and wide-angle cameras for visible wavelength imaging
	Ultraviolet Imaging Spectrograph (UVIS)	Measures ultraviolet light to determine temperatures and compositions
	Visible and Infrared Mapping Spectrometer (VIMS)	Measures reflected and emitted radiation to determine structures, temperatures, and compostions
MAPS	Cassini Plasma Spectrometer (CAPS)	Measures energy and electrical charge in Saturn's magnetosphere
	Cosmic Dust Analyzer (CDA)	*In-situ* measurements of particulates in the Saturn system
	Ion Neutral and Mass Spectrometer (INMS)	Measures positive ion and neutral specices to determine compositions in atmospheres, magnetospheres, and particulates
	Magnetometer (MAG)	Measures magnetic fields
	Radio and Plasme Wave Science (RPWS)	Measures electron density and temperatures of plasma and electric and magnetic fields
Microwave Remote Sensing	RADAR	Uses altimetry, radiometry, backscatter, and imaging to study satellite surfaces
	Radio Science Subsystem (RSS)	Investigates atmospheres, gravity fields, and rings via spacecraft radio transmissions

Table 1. Cassini Instruments.

IV. Science Objectives

The proximal orbits represent a unique opportunity for the Cassini mission to gather unprecedented science about the Saturn system. Proximal orbit measurements will include: (1) determinations of the higher order moments of both the gravity and magnetic fields to constrain Saturn's interior structure and possibly its internal rotation rate; (2) measurement of Saturn's ring mass, currently uncertain by about an order of magnitude; (3) *in-situ* measurements of Saturn's ionosphere, innermost radiation belts, and D ring, and possibly *in-situ* measurements of Saturn's auroral acceleration region; (4) high resolution studies of the main rings; and (5) high resolution Saturn atmospheric studies. The periapse orientation near local solar noon and south of the ring plane allows high-phase, high-resolution imaging, as well as Earth and solar occultations, of the main rings. The approach to periapse is over the northern hemisphere for inbound observations of the sunlit rings. Outbound trajectories provide excellent views of Saturn's southern aurorae.

A. Saturn's Interior, Magnetic and Gravitational Fields

The proximal orbits will allow Cassini to study Saturn's magnetic and gravity fields while in close proximity to the planet. The Magnetometer will make high-resolution measurements of the magnetic field inside of 5 R_S to determine the higher order coefficients of the magnetic field to degree 6, which may allow a determination of the depth of Saturn's metallic hydrogen core to be made and is important for understanding the dynamo mechanism. A tenet of dynamo theory is that a planetary dynamo cannot sustain an axisymmetric field. Yet, Cassini measurements of Saturn's intrinsic magnetic field to date have not shown any significant deviations from axisymmetry. The proximal orbit measurements are Cassini's best chance for determining the rotation rate of the planetary interior. This is key to interpreting the gravity field, which RSS will measure. Data from six gravity passes will allow the estimation of Saturn zonal gravity harmonics up to degree 10 with an accuracy of $< 10^{-8}$, at least two orders of magnitude better than current model values for J10. The low-order harmonics of the gravity field give information about the mass of the core and possible internal layering. The high-order harmonics give information about the currents deep in the fluid interior.

B. Mass, Composition, and Structure of Saturn's Rings

The proximal orbits (along with the preceding F ring orbits) will enable observations that can provide new insight into several key questions surrounding Saturn's rings. During these orbits, RSS will measure the ring mass directly via occultations performed in a nearly ideal orbital alignment. Knowing the mass of Saturn's rings will help settle important questions regarding their age and evolution. It is thought, for instance, that a low mass for the rings will imply a younger ring system.

The proximal orbits allow *in-situ* sampling of smaller ring grains. Deep within Saturn's inner magnetosphere, the rings are continually eroded by magnetospheric plasma. Mutual collisions and impacts from micrometeoroids also slowly grind down ring particles. Some of the debris thusly generated migrates inward where it can be sampled directly by Cassini. Small, micron-sized grains originating from the main rings of Saturn quickly develop an electric charge and may be directly detected by CDA. The sputtering of ring particles by magnetospheric plasma releases ions and neutral molecules which can be detected by INMS as they drift inward, permitting the direct measurement of ring particle composition. Though it has long been known that the rings are largely composed of contaminated water ice[3,4,5], rings scientists do not yet know what the contaminants are or where they originate. CDA and INMS observations will bring invaluable new data to bear on this question.

When Cassini entered orbit at Saturn, it flew directly over the main rings, coming closer to them than it ever has since. In so doing, its cameras caught tantalizing glimpses of new structures in the rings, such as that shown in Fig. 5, providing a preview of the images that will be obtained during the proximal orbits. This unique viewing geometry may very well reveal new ring features and structures. There are even plans to observe the rings with the RADAR instrument, which will take advantage of the unprecedented spatial resolution to carry out unique observations at microwave wavelengths.

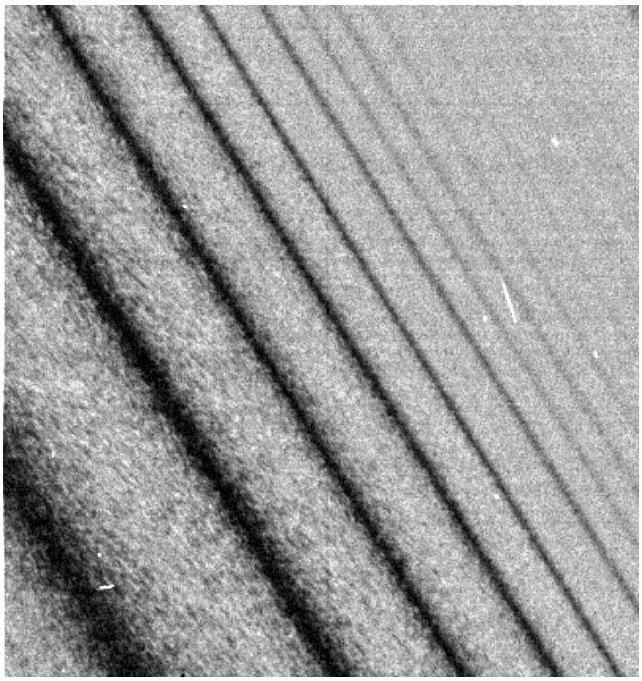

Figure 5. During Saturn Orbit Insertion, Cassini's cameras captured this close-up image of density waves in Saturn's A ring. Density wave troughs appear dark; whereas density peaks, where ring material bunches up, are bright. Scientists dubbed the striations discovered in SOI images, which are most visible in the density wave peaks at the lower left, "straw". Proximal orbit images will enable further studies of such features (image credit: NASA/JPL/Space Science Institute).

C. In-situ Atmospheric and Radiation Studies

For the first time, Saturn's ionospheric composition will be investigated with *in-situ* measurements of electron density and temperature by RPWS, as well as dust composition by CDA. INMS will be able to directly sample the composition of Saturn's ionosphere and upper atmosphere, which will allow for comparison of this *in-situ* data to compositional information derived from spectral observations and occultation experiments.

During Saturn Orbit Insertion, MIMI saw a signature of a radiation belt inside the D ring, but has not been able to further study the belt since then because of the spacecraft's orbital geometry[6]. Flying inside the D ring, MIMI and RPWS will search for evidence of trapped magnetospheric plasma to determine whether or a not a radiation belt exists between the D ring and the upper atmosphere. The proximal orbits will also provide the best opportunity for finding and studying lightning by searching for their characteristic radio waves with RPWS.

V. Environmental Hazards and Engineering Constraints

The proximal orbits' geometry and Saturn's environment place a number of engineering constraints on spacecraft operations and planning of science observations. Spacecraft pointing is constrained because of the orbital geometry and bright body issues caused by Saturn and the Sun. Two aspects of the Saturn environment[‡], ring dust particles and Saturn's atmosphere, pose potential hazards to the spacecraft during the proximal orbits. Ring dust particles could impact and damage the spacecraft while the atmosphere could cause the spacecraft to lose control authority or suffer thermal damage. Thus, the project has analyzed the Saturn environment and impacts of the orbital geometry to determine appropriate mitigations.

[‡] While not discussed in detail here, the project is also studying the radiation levels that may be encountered during the proximal orbit periapse passages. Initial studies suggest that the radiation may not be any worse than the levels the spacecraft has already encountered in the Saturn system. A radiation hazard would likely not have any impact on the types of science observations done during the periapse passages, but could result in modifications to flight software error monitor thresholds and anomaly responses.

A. Target Motion Compensation

The orbital geometry of the proximal orbits poses challenges to science observation planning. The ORS, RSS and RADAR instruments require the spacecraft to point their instruments' field-of-view to the desired target. The spacecraft must track the target for the duration of the observation and, thus, must be able to compensate for its motion relative to the target. The spacecraft can track a target as long as its angular velocity about the target does not exceed the capabilities of the reaction wheels or the thrusters. The close distances to Saturn and the high velocity make target motion compensation (TMC) problematic during the proximal orbits. Saturn surface and ring features cannot always be tracked throughout a periapse crossing because the needed TMC exceeds the attitude control capabilities of the spacecraft. As shown in Fig. 6, Saturn surface features located between 24°N and 36°S latitudes cannot be continuously tracked during a periapse crossing. Restrictions vary on each orbit because TMC is affected by both distance and velocity, so crossings that are farther away from a surface feature would be able to track a feature for longer than closer crossings. The amount of time for which targeting is not possible depends on the target, but is on the order of minutes or less.

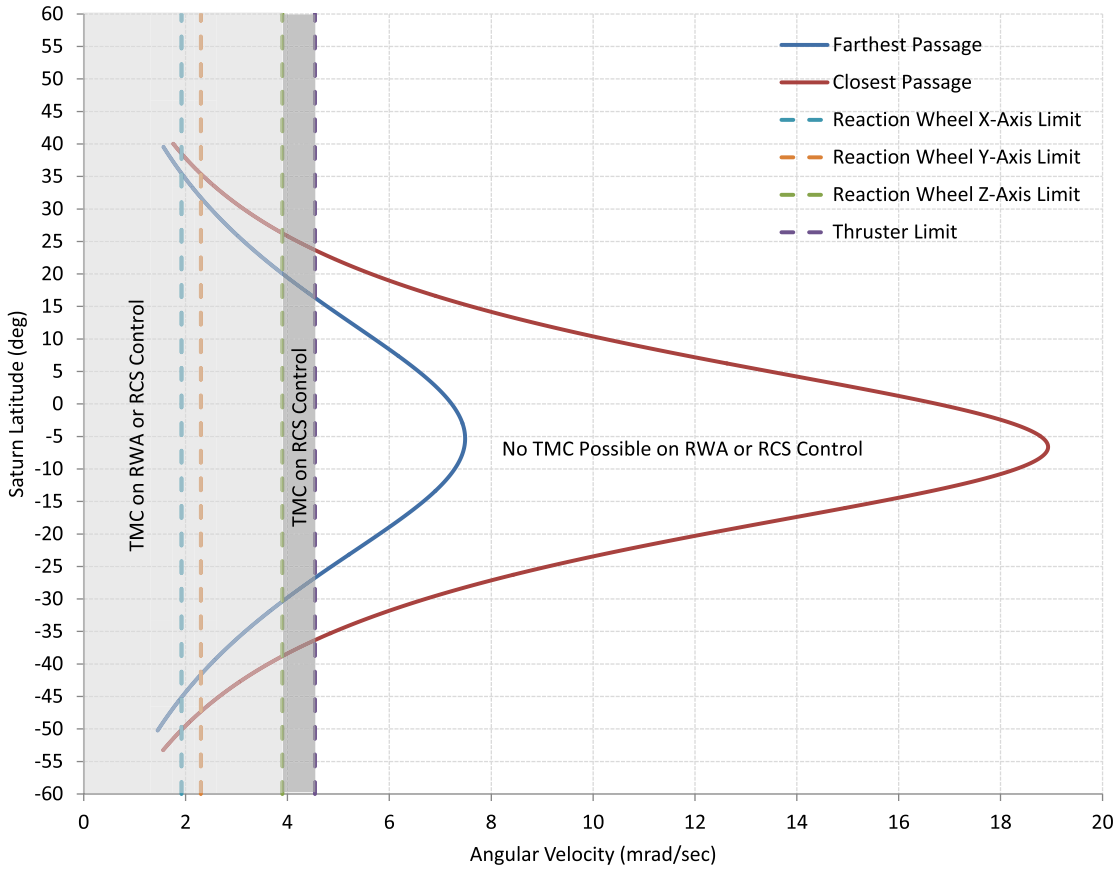

Figure 6. TMC for Saturn Surface Feature Tracking.

B. Bright Body Constraints

Bright bodies, such as the Sun, have always levied pointing constraints on the spacecraft. The stellar reference units (SRU) and the CIRS and VIMS radiators are sensitive to bright bodies and must not be directly pointed in the direction of the bodies. CIRS and VIMS are cooled by radiators which emit excess thermal energy to space. When the radiator is heated, the instrument's detectors are forced to a temperature that is higher than nominal and the ability of the instrument to collect science data is compromised. Pointing the radiators towards the Sun or Saturn can lead to such heating. The higher the temperature excursion, the less the instruments are able to compensate for the heating. Beyond an established threshold, the health of the instruments is compromised. The SRU's ability to provide attitude information is also compromised when a bright body enters the detector's field-of-view.

The unique geometry of the proximal orbits means bright body constraints imposed by both the Sun and Saturn must be considered when planning science observations. During periapse passage the Sun and Saturn are on

opposite sides of the spacecraft, which may make it difficult to find a spacecraft attitude that does not point a sensitive component towards a bright body. Use of the SRUs can be suspended for up to five hours to avoid bright body violations; during that time gyros are used instead. CIRS and VIMS attitudes must be managed to avoid excessive heating.

C. Dust Hazards

Saturn has the most extensive ring system of any planet in our Solar System. The dust particles associated with the rings can pose a danger to the spacecraft. In the early 1990s, the Cassini project initiated an effort to assess the hazard posed by ring dust particles to the spacecraft[7]. The effort has continued to date, with ring dust models frequently updated with the latest ring science collected by Cassini. The result of this effort has been the identification of regions the spacecraft can traverse at minimal risk and protective measures that can further reduce the risk of damage to the spacecraft. Understanding the presence of dust interior to the D Ring was of utmost importance in proving the feasibility of the proximal orbits.

The main areas of vulnerability to dust damage on the Cassini spacecraft are the main engines and select areas of the electronics bus[7]. Parts of the electronics bus are behind a single layer of aluminum or thermal louvers and penetration or spalling of the aluminum plate could damage the electronics. A dust impact on one of the main engines could cause the engine to fail and, in the most catastrophic case, a burn-through in one engine could cause the loss of both main engines[7]. Two methods are employed to protect the vulnerable areas of the spacecraft from dust impacts: 1) a main engine cover that can be closed over the engines when the spacecraft crosses through dusty regions. 2) For the riskiest dust hazards, the spacecraft's HGA is turned into the direction of the oncoming dust to protect the spacecraft bus.

Since no *in-situ* D ring data exist, analyses have been based on remote sensing data. Cassini images of the D ring have been used by scientists to look for sunlight scattered by dust particles and to estimate the amount of dust present. During the initial design of the proximal orbits, the region below 65,000 km from Saturn center was believed to be free of the most dangerous D ring dust particles. The proximal orbits trajectory was designed using this upper limit, with a few of the orbits passing fairly close to the 65,000 km limit. However, data collected in 2012 (at better viewing geometries than previous observations) indicated that more dust particles than previously thought existed inside the D ring. An assessment of this new data versus the proximal orbits trajectory found that more than half of the proximal orbits would have to assume a protective attitude using the HGA to shield the spacecraft from dust impacts. Since the HGA and all instruments are body-fixed to the spacecraft, the protective attitude significantly limits the science data that could be collected during those periapse passages. The project elected to further study the new D ring data and also redesign the proximal orbits trajectory to lower the affected orbits out of the riskier region. After studying the D ring data, a new limit of 64,000 km was set.

As seen in Fig. 3, several of the proximal orbits pass above 64,000 km, the upper edge of the gap. While a boundary of 64,000 km had been set for planning purposes, in reality there is not a clear demarcation where dust particles no longer exist. Dust particles may exist throughout the gap Cassini will traverse, but it is believed that their abundance drops with decreasing distance to Saturn. After analysis and consultation with Cassini Rings scientists, it was determined to be acceptable for the spacecraft to cross the gap above 64,000 km as long as the protective attitude is assumed. However, the majority of the proximal orbits now cross below the upper limit, so the redesign was successful in lowering the dust hazard risk to the spacecraft and reducing the impact to science, as fewer orbits require the protective attitude.

D. Saturn Atmosphere

Saturn's atmosphere defines the inner boundary of the region the spacecraft can safely traverse. Thus, the project has made a considerable effort to model the atmosphere and understand its impact on the spacecraft. Data from UVIS stellar occultations has been instrumental in determining the temperatures, composition, and density of the atmosphere. Additional observations of Saturn's atmosphere will be made in the remaining years of the CSM and new data folded into the atmosphere model. Any changes in the model will be closely analyzed to ensure proximal orbit plans continue to adequately address any hazards posed by the atmosphere.

1. Attitude Control

The torque from Saturn's atmosphere on the spacecraft poses a risk to the spacecraft's ability to maintain attitude control during the periapse passages. If attitude control is lost, the spacecraft will be unable to point to specified targets or safing could occur; in both cases science data would be lost. Analysis, done by the Cassini attitude control team, of the atmospheric torque imparted on the spacecraft determined that the closest the spacecraft can fly to Saturn is 61,750 km from Saturn center before losing control authority. As can be seen in Fig. 3, the spacecraft does

not cross below this boundary during the proximal orbits. Even within the gap, there are attitude control concerns. Cassini has two methods of attitude control: reaction wheels or thrusters. The reaction wheels cannot counteract as much torque as the thrusters, thus it must be determined which periapse passages can use the reaction wheels and which must use the thrusters. This is important not only for spacecraft safety but also for science because some observations require reaction wheel control. The boundary between reaction wheel control and thruster control was determined to be ~62,000 km. Thus, only the last five proximal orbits are required to use thrusters for attitude control. However, it is possible that several of the first proximal orbits will also be done on thruster control out of an abundance of caution since the spacecraft will be encountering a new region for the first time.

The Saturn atmosphere model was also used to determine where Saturn impact should be targeted to ensure the spacecraft would impact the planet. Analysis revealed this boundary to be ~60,745 km. As can be seen in Fig. 3, the impact orbit was targeted far below this boundary to guarantee spacecraft disposal. There is a 1,005 km-wide area between this boundary and the lower edge of the safe gap. This area must be avoided because atmospheric torque is too high for the spacecraft's attitude control capabilities and trajectory deviations could occur. Significant atmospheric drag would alter the trajectory of the spacecraft and, thus, Saturn impact may no longer be guaranteed. Therefore, the proximal orbits were designed to avoid this area.

2. Aeroheating

Saturn's atmosphere combined with the high velocities (up to 34 km/s) of the proximal orbits pose a thermal concern to the spacecraft and instruments. Aeroheating can raise hardware temperatures to unsafe levels during the periapse passages. The Cassini thermal team assessed the feasibility of the proximal orbits by determining the levels of aeroheating that will be encountered and identifying the most sensitive areas of the spacecraft. The analysis revealed that any crossing closer than 62,730 km to Saturn would result in aeroheating, with the critical aeroheating period centered 20 minutes around closest approach. The analysis also identified thermally acceptable spacecraft attitudes that could be used for these crossings. Attitudes that place the HGA or –X axis into the velocity ram direction were found to be acceptable; however pointing the +X axis into velocity ram resulted in large temperature increases of sensitive components. The radiators and other components of several ORS instruments are on this side of the spacecraft. Thus, the proximal orbits were found to be thermally feasible as long as spacecraft attitudes are restricted to those that do not overheat components. Aeroheating is only a concern on the final five proximal orbits, and attitude restrictions will impact science data collection somewhat during these periapse passages. As science observation planning matures more spacecraft attitudes will be investigated to further refine the aeroheating analysis.

E. Impact on Science Observations

The environmental hazards and orbital geometry place a number of engineering constraints on the spacecraft and the science observations. All of the various constraints must be taken into account when planning science observations. Overlaying the engineering constraints imposed by the environmental hazards on the proximal orbit periapse passages, as shown in Fig. 7, illustrates on which passages science observations may be constrained.

In order to proactively identify as many of these science planning challenges as possible, the Cassini project has begun to study the types of science observations that could be done and simulate periapse (within 1-2 days of closest approach) activity sequences. The simulated sequences have been of great utility as they have given the Cassini project an advanced look at some of the science observations and how the engineering constraints will affect them.

Since all instruments are body-fixed to the spacecraft, pointing restrictions can inhibit science observations when instruments are pointed on non-compatible sides of the spacecraft. For example, the *in-situ* detection of dust particles and magnetospheric ions residing between Saturn's atmosphere and the D ring will be a very high priority science goal during the proximal orbits. To collect the data, CDA and INMS must be pointed in the direction of the incoming particles. However, following the ring plane crossings, this attitude points the CIRS and VIMS radiators (mounted on the opposite side of the spacecraft) towards Saturn. Since Saturn is a bright body holding this attitude for too long will result in the CIRS and VIMS instruments being heated to unacceptably high levels.

As mentioned previously, some science observations must be done on reaction wheel control, as opposed to thruster attitude control, because of the fine-scale pointing control they require. One such investigation is the RSS gravity observations; these measurements must be done on wheels and therefore cannot be done during the last five proximal orbits when thruster attitude control is required. Conversely, some science observations, such as RPWS lightning observations, require the use of thruster control, as the wheels generate unacceptably high levels of electromagnetic interference. Such observations could be executed on the final five orbits.

Proximal orbit planning will require determining an appropriate science trade-off between conflicting observations and how to allocate science observing time with respect to the engineering constraints. Some science

observations may be limited to periapse passages where certain engineering constraints do not occur, while others may be constrained to certain times within the periapse passage in order to avoid violating constraints. These types of requirements must be taken into account during the science observation allocation process.

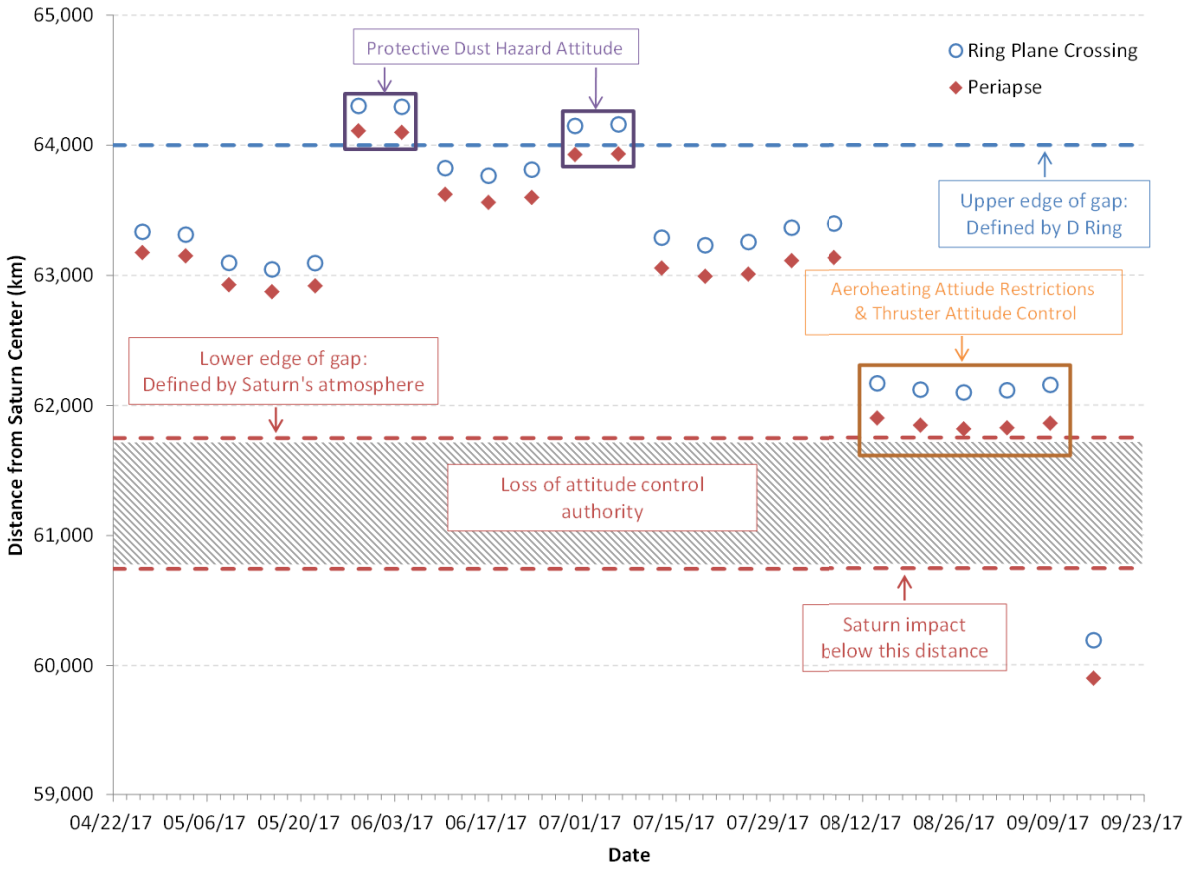

Figure 7. Environmental Hazards Impact on Proximal Orbit Periapse Crossings.

VI. Planning Tools and Processes

The project has also undertaken an assessment of the tools and processes used to plan science observations and sequences. Studies have focused on how these tools and processes will be used and if any modifications are needed before they can be applied to proximal orbit science planning.

A. Planning Software Modifications

The sequence simulations have revealed potential software issues and prudence dictates that software used for detailed planning undergo significant review. At the outset of the mission, spacecraft engineers did not anticipate the geometries that the spacecraft will experience during the proximal orbits. As a result, some of the project's planning software may not function as intended during this mission phase, even though it has served very well previously.

One function of Cassini's planning software that must be addressed is the assessment of flight rule violations. Before they are uplinked, sequences to be executed by the spacecraft are routinely assessed against the dozens of flight rules that are intended to maintain the health and safety of the spacecraft and its many subsystems. Flight rule violations are assessed on a local scale by the science teams who design their own observations. The Science Planning and Sequencing Team, which, among other things, is responsible for designing downlink activities and establishing safe waypoints to be used between science observations, does a similar check on the activities they design. The primary tool for this purpose is the Pointing Design Tool (PDT); PDT is also used to ensure that teams allocate adequate turn time and margin between successive spacecraft activities. Attitude control engineers use the Kinematic Predictor Tool (KPT) to assess complete sequences (built from merged inputs provided by the science teams) for spacecraft pointing issues and violations. Some of the algorithms used by KPT and PDT to assess flight

rule violations are poorly suited to the new proximal orbit geometries. Owing to the critical nature of these flight rules, a review of them and the algorithms used to assess them will be essential to Cassini's success during the proximal orbits.

An example of these issues is the flight rules that protect CIRS against large thermal excursions. CIRS observes Saturn in the thermal infrared, at wavelengths ranging from 7 – 1,000 microns[8]. As such, CIRS is very sensitive to heating events. However, it was never envisioned that Cassini would routinely come within 2.4 R_S from the planet. The model PDT uses to predict CIRS thermal excursions ceases to calculate heating from the planet inside this range. Moreover, the models that both KPT and PDT use to determine CIRS heating calculate the incident thermal flux from Saturn and the rings assuming the rings to be always face-on from Cassini's vantage point. This model, while simple to implement, is needlessly conservative, which in turn would hamper the ability to take science observations at a point in the mission when engineering margins will have to be pushed even further towards their limits. Fortunately, the CIRS team has made significant progress in producing a more realistic thermal model for future inclusion with Cassini science planning software and which will also continue to protect the instrument.

Another aspect of Cassini's planning software that will be subject to problems imposed by the geometry of the proximal orbits is targeting of the spacecraft's instruments. When creating observation designs with PDT, Cassini scientists select one of a number of targeting modules, each with its own set of options, to pinpoint some location on a body or set of bodies for their science observations. For example, users can select a module that will target a specific longitude and latitude on a planet. PDT and KPT, in turn, invoke a software suite known as the Inertial Vector Propagator (IVP) Tool that interprets these targeting instructions to produce a series of vectors. The spacecraft uses these vectors to execute the pointing specified in the science observation design.

However, some of these targeting modules make use of algorithms that will not work when the spacecraft comes as close to the planet as it will during the proximal orbits. A prime example of this is a ring targeting module which is routinely used to target the ring ansae, the loci of points where the spatial resolution in the ring plane is best and the foreshortening arising from the oblique viewing geometry is minimized. The definition of the ansae in Cassini's planning software does not converge when the spacecraft is within the cylinder defined by the rings' radial extent (and aligned with the planet's spin axis); the spacecraft's trajectory will take it inside this cylinder on every proximal orbit. With no way to communicate the definition of the ring ansae to IVP, Cassini scientists will be unable to directly target the ring ansae during the few hours before and after closest approach to Saturn. Similar problems exist for some of the other targeting modules currently being used by Cassini scientists.

Although three years remain until the start of the proximal orbits, there will not be time to address every software issue that is found. All of the issues that are uncovered will be prioritized according to the need to address the issue, as well as the workload required to address it. Some problems will be fixed because not doing so may jeopardize the final phase of the Cassini mission. Others will be fixed because the solution represents a minor amount of work. Yet other issues will have to be resolved via the use of suitable workarounds, such as the use of alternative targeting modules, that allow science objectives to still be achieved even with the limitations of the tools.

B. Science Planning and Sequencing Process Changes

The unique characteristics of the proximal orbits, such as the high velocities and ballistic trajectory, necessitated modifications to the science planning and sequencing process. The project has made changes to these processes in the past, with the most significant overhaul of the processes occurring during the transition from the PM and CEM to the CSM[9]. The aim of the overhaul was to simplify operations due to the need to reduce staffing levels. These CSM processes, summarized below, form the backbone of the processes that will be used for the proximal orbits. However, small modifications have been made in order to address the challenges posed by the final mission phase.

During the CSM overhaul, early-stage science activity planning was reengineered to include a "pre-integration" process designed to focus limited resources on each science discipline's highest priority objectives. During the pre-integration process, each Discipline Working Group (DWG) was allocated 400 observing hours to spend on its highest priority and/or most geometrically-sensitive observations across the entire CSM, up to the start of the F Ring orbits. These activities, called Pre-Integrated Events (PIEs), were submitted by each DWG and conflicts were then resolved during a negotiation process between DWG representatives. After the PIE conflicts were resolved, the periapse portion (defined to be within 18Rs of Saturn) of each orbit was assigned to a specific DWG for the purpose of filling in the rest of the timeline with discipline-focused activities[§]. This latter part of the process, called integration, continues today on a just-in-time basis, completing prior to the start of each sequence development process.

[§] Most apoapse portions (outside of 18Rs) of each orbit do not include any PIEs and have a multi-discipline focus.

The pre-integration process significantly reduced the labor-intensive, multi-discipline negotiations that took place during integration in PM and CEM, and, as a result, CSM integration is a much more efficient process. Also, by restricting each periapse segment to a single discipline (with the exception of the limited number of approved PIEs), there is less optimization and lower density of activities in the science timeline and both the total number and complexity of science activities have been reduced. Simplification of the science timelines mitigates labor-intensive tasks downstream.

The CSM sequence implementation process also underwent a rigorous overhaul to accommodate staffing reductions. Given the simplification and reduction in number of science activities, it was possible to compress the CSM sequence development schedule. At the same time, the execution time of each sequence was doubled. As a result, 10-week sequences are now implemented in less time than was formerly required for 5-week sequences, and there are only three overlapping sequence processes occurring simultaneously (half as many as in PM and CEM)[9].

The modifications described above have provided a firm foundation upon which to base the science planning and sequencing processes for the proximal orbits. A few additional modifications to the pre-integration and sequencing processes are planned to better address some of the unique characteristics of the proximal orbits.

For pre-integration, the basic concept of PIEs and discipline-focused orbit segments remains largely intact, with a few notable differences: (1) a periapse segment was re-defined to mean a period within 12-36 hours of closest approach, instead of the previous definition of within 18 R_S of Saturn, which would encompass almost all of a proximal orbit. (2) Due to the unique geometries of these orbits that enable once-in-a-lifetime opportunities to address fundamental science objectives, there will be a greater emphasis on coordinated observations in support of multi-discipline priorities and more time will be allocated in support of Saturn, rings, and MAPS observations than to Titan and icy satellites (due to the lack of close satellite encounters in the proximal orbits). (3) Because the spacecraft will be traveling at extremely high velocities (with challenging pointing constraints) at closest approach, this critical time period can only be used effectively for a limited number of observation types. As a result of these differences, prior to the start of pre-integration DWG representatives will negotiate and allocate just the ~two-hour period (+/- one hour) right at closest approach for each proximal orbit. The expectation is that these periods will be allocated primarily to MAPS and RSS gravity activities. These two-hour periods will be integrated into the timeline like PIEs but won't be counted against any discipline's PIE-hour allocation. In addition, DWG representatives will meet to allocate approximately six entire periapse segments dedicated to RSS gravity observations.

Once the direct allocations for RSS gravity segments and the two-hour closest approach periods have been negotiated, the nominal pre-integration process will begin. However, it too has a notable difference from what was done previously due to the fact that many science objectives during these orbits can be addressed via an allocation of a certain <u>number</u> of orbits vs. an allocation of <u>particular</u> orbits (or individual PIEs) because of the repeating geometries within the proximal orbits. It is hoped that some process efficiency can be realized by focusing attention during pre-integration for the proximal orbits on segment or orbit allocations and only going down to the PIE-hour level as needed for unique observations that aren't readily captured by multiple opportunities within orbits of similar/repeating orbital geometries. While pre-integration streamlines the detailed integration process, negotiating at the PIE-hour level is in itself a time-consuming activity. For simplicity, the same number of PIE hours has been allocated to all disciplines. However, the bulk of the orbit segments (and, therefore, the bulk of the observing time) will be allocated to the Saturn, Rings and MAPS DWGs, reflecting the balance of critical science priorities for the proximal orbits.

For the proximal orbits, a modification to the sequencing process is required due to the fact that the spacecraft will be flying a ballistic trajectory after the flyby of Titan that initiates the proximal orbits. Once the spacecraft is on the ballistic trajectory, no further maneuvers are required during the remaining 22 orbits to ensure impacting Saturn for spacecraft disposal at the end of mission. Current navigation strategy in the CSM is to perform up to three maneuvers per orbit which continually move the spacecraft back to the pre-planned reference trajectory and keeps spacecraft pointing plans on target. Without regular maneuvers in the proximal orbits, pointing errors will grow rapidly and significantly impact science targeting. The 10-week sequence execution period used in CSM exacerbates this problem because of the time interval between the final incorporation of new spacecraft and planetary ephemeris files into pointing designs and when the pointing commands are actually executed onboard the spacecraft, allowing ample time for pointing errors to grow.

Thus, the project evaluated a number of modifications to the sequencing process to mitigate the pointing error growth challenge. The first option considered was to revert back to shorter sequence durations as used in PM and CEM. However, this option was deemed infeasible due to the lower staffing levels available in CSM. An increase in the number of updates to pointing commands during sequence execution and modifications to definition and packaging of pointing commands was also considered. However, these options increase the risk of command errors and spacecraft safing, as well as straining staffing resources. The trade study of all possible options led to selection

of a modification to the existing sequence development process by incorporating updated spacecraft and planetary ephemeris files later in the process so that pointing vectors are defined with the most current information available. As a result, the length of time pointing errors are able to propagate during execution is cut in half and pointing error magnitude is decreased to an acceptable level. In addition, the 10-week sequence will be developed as two 5-week parts, which allows another opportunity to ingest updated ephemeris files for the second part closer to when it will be uplinked (which occurs during execution of the first 5-week part). This is different from reverting back to separate 5-week sequences, as used in PM and CEM, since both sequence parts are developed during one sequence development cycle. This approach limits modifications to the existing process while providing a mechanism to keep pointing errors below the threshold required for science.

The project has undertaken a study of adding a small number of maneuvers to the proximal orbits for the sole purpose of keeping pointing uncertainties low. However, the project will proceed with changes to the sequence process in order to still be able to compensate for pointing errors in the event that additional maneuvers will not be executed (for example, if sufficient propellant reserves are not available).

VII. Conclusion

The proximal orbits represent an exciting closing chapter to the Cassini mission with the opportunity to gather unique science data on the Saturn system. However, they also represent an orbital geometry and environment that the Cassini project never anticipated encountering. As the first step in planning for the final mission phase, the project has made considerable progress in characterizing the proximal orbits and identifying the challenges that must be addressed. Studies have focused on the Saturn environment and designing a proximal orbits trajectory that avoids the worst hazards posed by the ring dust particles and the atmosphere. Other studies have focused on the type of science observations that will be done and how they can be implemented with current software tools and processes. This early work lays an important foundation that will guide the detailed science activity planning and bring the proximal orbits to fruition.

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