The Cassini Grand Finale Mission: Planning for a New Mission Environment

Nancy Vandermey
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-5832
nancy.vandermey@jpl.nasa.gov

William Heventhal
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-7836
william.m.heventhal@jpl.nasa.gov

Trina Ray
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-8655
trina.l.ray@jpl.nasa.gov

Abstract—**The Cassini F-Ring & Proximal Orbits (FRPO) is a new and unique mission; to ensure the highest priority science gets implemented, the POST (Proximal Orbit Science Team) was created to pre-allocate the time around periapse for all 22 proximal orbits. The F-ring orbits, and proximal time outside of POST, were handled similar to Cassini's Solstice Mission using the Pre-Integrated Event (PIE) process. The new and unique properties of the spacecraft's trajectory required much forethought to be flown safely while still planning for the most and best science return possible.**

Some ring-plane crossings (RPX) will be protected against dust impacts by turning the high gain antenna (HGA) to the dust RAM direction (HGA2RAM). If on the first proximal RPX higher than expected dust readings are seen then the Project Office may choose to require more (all) subsequent RPX to be HGA2RAM, implemented via a real-time command overlay for uplinked sequences.

The pointing uncertainties will be larger than usual after the final targeted flyby; some of the process changes to address this include adding extra orbit trim maneuvers (OTMs) (fuel permitting) to resync to the reference trajectory and reduce pointing uncertainties; and movable blocks of commands to be used for some periapses where atmospheric drag may cause large timing shifts

Changes made for FRPO to address perceptions that these sequences will be hard to implement include requiring early pointing designs (during integration) for certain types of observations, requiring teams to check early on that they can turn to and from their observation attitude, and that their attitude is safe, and adjusting the Implementation process to give more time for science observation designers.

This paper will discuss these process changes and lessons learned so far.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. SCIENCE OVERVIEW 3
3. FRPO CHALLENGES 4
4. CONCLUSIONS 9
APPENDICES 10
ACKNOWLEDGEMENTS 10
REFERENCES 10
BIOGRAPHY 11

1. INTRODUCTION

On September 15, 2017, after almost 20 years of flight, Cassini will end its glorious mission at Saturn and ultimately meet its demise as it plunges into the ringed planet's atmosphere [1]. This is being done to satisfy the planetary protection requirements imposed on Cassini. This is necessary in order to dispose of the spacecraft in such a way such that it does not pose a threat to Titan or Enceladus, which may hold evidence of precursors of life as they have been determined to hold vast internal oceans or surface lakes.

Cassini, a joint NASA / ESA mission, was launched on October 15, 1997 in order to carry out a four-year orbital mission (Prime Mission) to study five areas relating to Saturn: the planet itself, the rings, Titan, other icy moons, and the magnetosphere. These 5 disciplines, and a cross-discipline group, were comprised of scientists both representing specific Cassini instruments and specialists in that discipline. The discipline working groups were used to analyze proposed extended mission trajectories, divide planning time into discrete chunks called segments, and design observations. Due to the missions' tremendous success and discoveries made, as well as an extremely healthy and robust spacecraft, Cassini was granted a two year mission extension (Equinox mission). Following the Equinox mission, Cassini was again granted another mission extension so that it could observe another season at Saturn (Solstice mission), which also included how Cassini was to end its mission by plunging into Saturn's atmosphere. Figure 1 shows the changing inclination and spread of targeted flybys throughout Cassini's long sojourn at Saturn. The last phase of the Solstice mission includes two focused orbital profiles; the F-Ring and Proximal Orbits (FRPO) (Figure 2).

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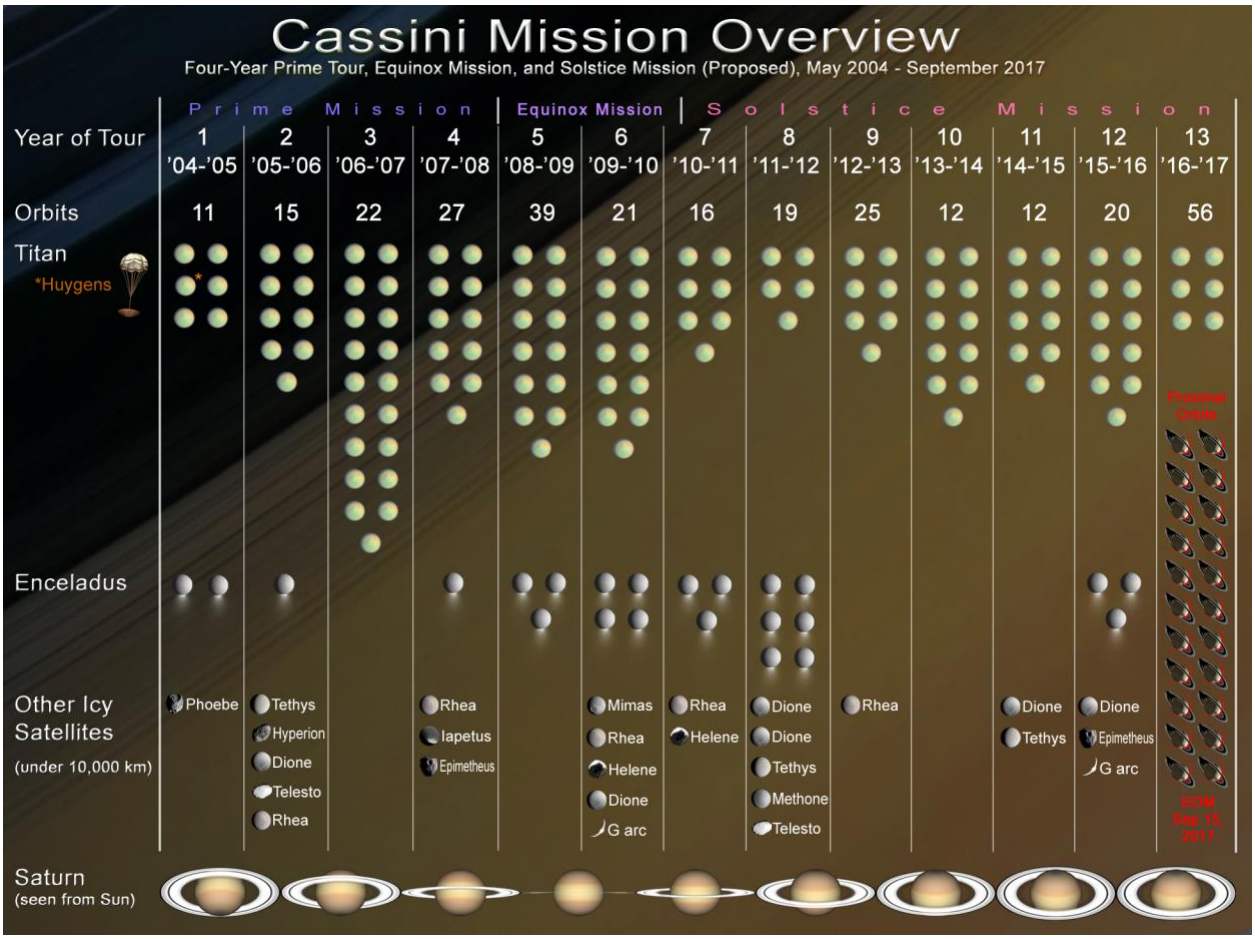


Figure 1. Cassini Mission Overview

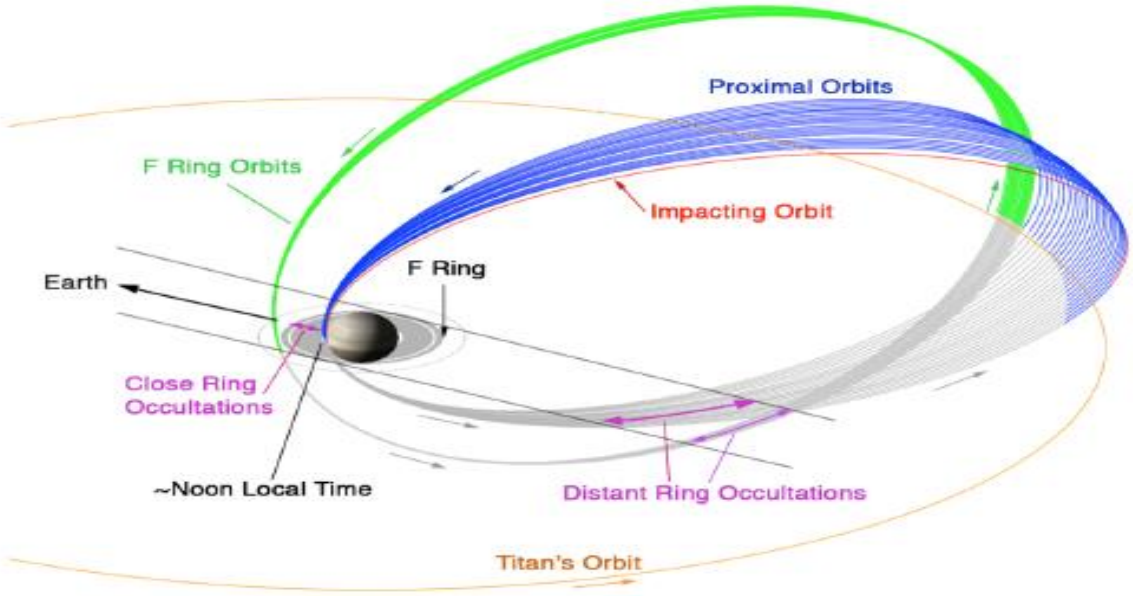


Figure 2. Cassini FRPO mission overview

This period starts with 20 highly inclined orbits just skimming the outskirts of the F-Ring. On April 22, 2017 Cassini will encounter its last targeted flyby of Titan (named T126) resulting in 22 orbits where the spacecraft will fly within a narrow ~2900 km corridor between the inner most D-ring and the top of Saturn's atmosphere (see Figures 3 and 4). While the T126 encounter itself will be rich with scientific observations, the rendezvous with Titan will also place the Cassini spacecraft on a ballistic trajectory that will ultimately culminate with the disposal of the spacecraft into Saturn's atmosphere approximately 5 months later.

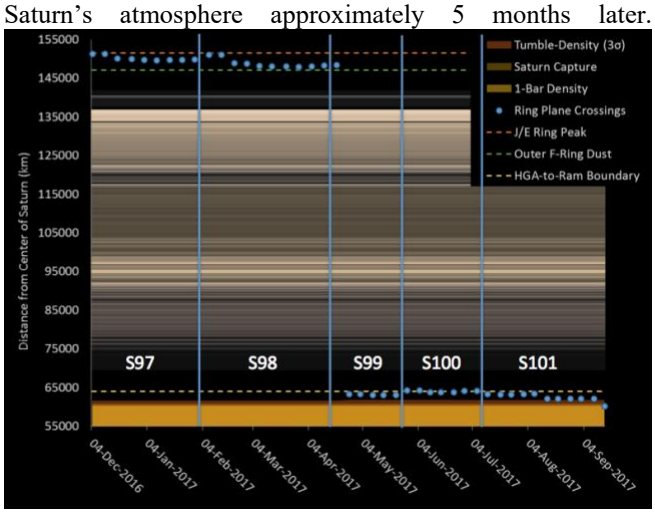


Figure 3. FRPO timeline

Many of the models in use needed to be updated with the incorporation of this new and exciting trajectory. When the spacecraft was being built and designed, there were never any plans to fly between the rings and the top of Saturn's atmosphere. Consequently many thermal and flight rule models were designed with this in mind. Statements to the effect that the model and flight rules were not valid inside of 2.1 Saturn radii (R_S) now needed to be updated, as the spacecraft would now be flying in this environment. This was complicated by the fact that the corporate knowledge with the original designers who developed the models in the late 1990s was no longer available.

The orbital period during the FRPO time frame will have been reduced to ~7 days (varies between 7.2 days – 6.5 days). This density of periapses led directly to an increase in the number of observations per sequence, raising workload concerns as the teams had decreased workforce after the transition from Prime to Extended mission phase

2. Science Overview

When the science teams first proposed the Solstice mission, a seven year period that would extend the life of the Cassini spacecraft out to the northern summer solstice of Saturn's year, the exact disposal of the spacecraft was not part of the plan. There were several suggestions that met the required planetary protection constraints: orbits that lasted 500 years without collision, trajectories that ejected the spacecraft to

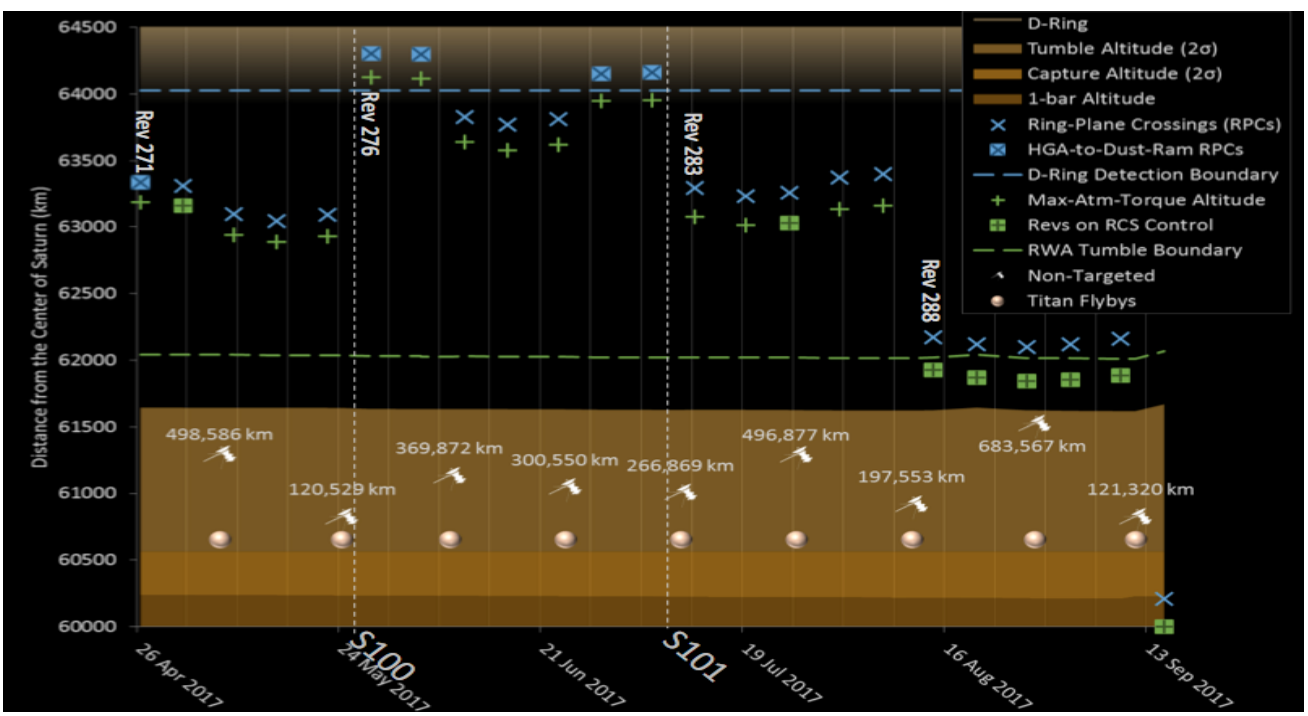


Figure 4. Proximal timeline

the Jupiter system, etc. The most compelling idea was a daring end of mission that would plunge the spacecraft in between the planet and the rings. This idea was compelling because there were several science objectives that had eluded the teams for many years.

First, the mass of the B-ring is still unknown to sufficient accuracy even at this point in the mission. The mass of the B-ring plays an important role in understanding the overall age of the Saturn ring system and has been elusive. Many stellar and solar occultations have probed the B-ring and modeled thermal behavior has been used to estimate ring mass. With the spacecraft transiting between the planet and rings, where the gravity of the rings pulls in the opposite direction to the gravity of the planet, we will finally be able to measure this elusive fundamental parameter of the rings. Radio Science is the prime instrument doing this investigation.

Second, the interior of Saturn, in particular the magnetic field of Saturn, has been puzzling for many years. The pole of Saturn's rotation is closely aligned with the magnetic pole of Saturn. The basic theory of planetary magnetic fields tells us that they can't be aligned or the field would collapse. Being able to pass from pole to pole closely gives us a chance to measure any small deviations and subtleties to Saturn's magnetic field and provide the theorists the data they need to substantially improve how to model gas giant magnetic fields. Data obtained may also determine if the rotation rate of the deep interior (where the magnetic field is generated) is different from the surface. In fact, just how deep inside Saturn is the dynamo that generates the magnetic field could be key to understanding this puzzling situation. The Magnetometer is the prime instrument doing this investigation. The Radio Science observations that probe the B-Ring mass are also ideally suited to add to our understanding of the interior of Saturn. We will be able to understand planetary formation and evolution, internal mass distribution, moment of inertia, differential rotation and depth of winds, tidal distortions and Love number.

Third, being able to get close enough to Saturn to use the Ion and Neutral Mass Spectrometer (INMS), an instrument designed to ingest material as we swoop through Titan's atmosphere will tell us about the composition of the atmosphere and perhaps dynamics as well. This is a unique opportunity to be able to sample in-situ Saturn's atmosphere.

There are easily half a dozen other science observations that can't be done in any other trajectory:

- In-situ composition (ions and neutrals) of Saturn's rings helps us understand ring age, composition, and ring evolution
- High resolution north and south thermal maps of Saturn, plus high resolution maps of turbulence and small scale structure with the best resolution in the mission
- Highest resolution scans of selected regions of the rings
- The intensity, composition, and energy spectrum of the trapped radiation between the D-Ring and Saturn's atmosphere. (one of the first discoveries of the Cassini mission, the material inside the D-Ring, will be one of the last things the spacecraft will get a chance to investigate)
- Unique RADAR passive and active scans of the rings
- High resolution imaging of the aurora

3. FRPO CHALLENGES

Pointing Uncertainties

Prior to the start of FRPO, the navigation philosophy was to use Titan's gravity to shape the orbit with three propulsive maneuvers designed to encounter Titan at a fixed time and location and drive the spacecraft trajectory back to this nominal reference trajectory. It is based upon this philosophy that all science observations were designed, factoring in the expected navigation uncertainties. With the proximal phase now on a ballistic trajectory and no longer including propulsive maneuvers to drive back to the reference trajectory, the science teams needed to alter their strategies in order to live with these new error sources.

The ballistic nature of the trajectory after the T126 Titan targeted flyby (which denotes the F-ring to proximal transition) resulted in increasing uncertainties in periapse time, which translates into along-track position errors, as displayed in figure 5. In the early proximal orbits these position uncertainties grew from 1000 km to 7000 km towards the end of the mission. While the mission has a live update capability to correct for pointing errors [2], input from instrument teams indicating 200 – 250 km (1σ) position errors would be the largest acceptable for science, which was exceeded early in the proximal revs.

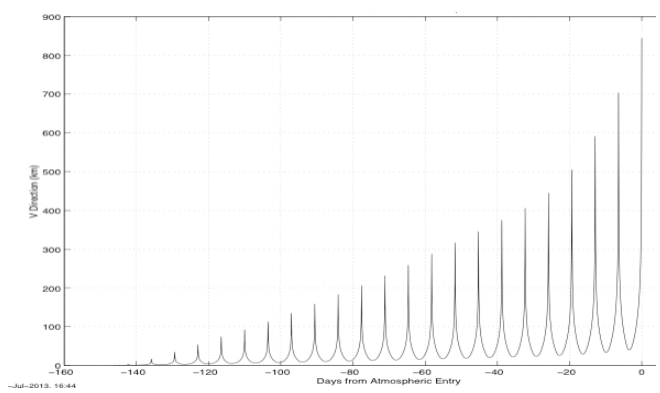


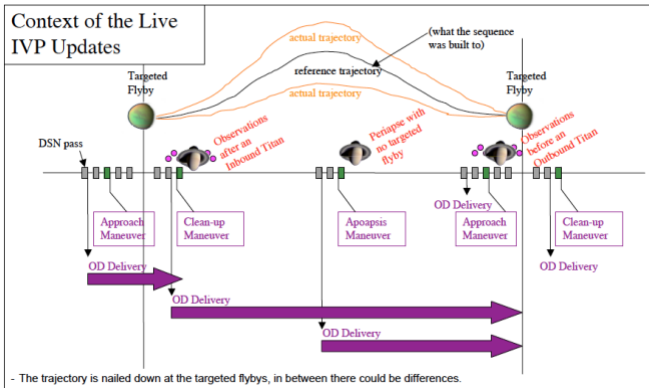
Figure 5. Pointing uncertainties

Figure 6. Live updates

Several options were proposed to address these escalating position uncertainties, including:

-shorter sequences to allow later NAV orbit determinations (OD)'s to be ingested. However the workforce impact was too great

-using the existing live update process (figure 6). Workload (increased OD frequency/building overlays for nearly every vector) were a concern, as all 20 F-ring periapses occur between the final two targeted Titan flybys



-ingesting an updated OD late in the sequence build process. Alleviates uncertainties in first part of 10 week sequence but not latter half.

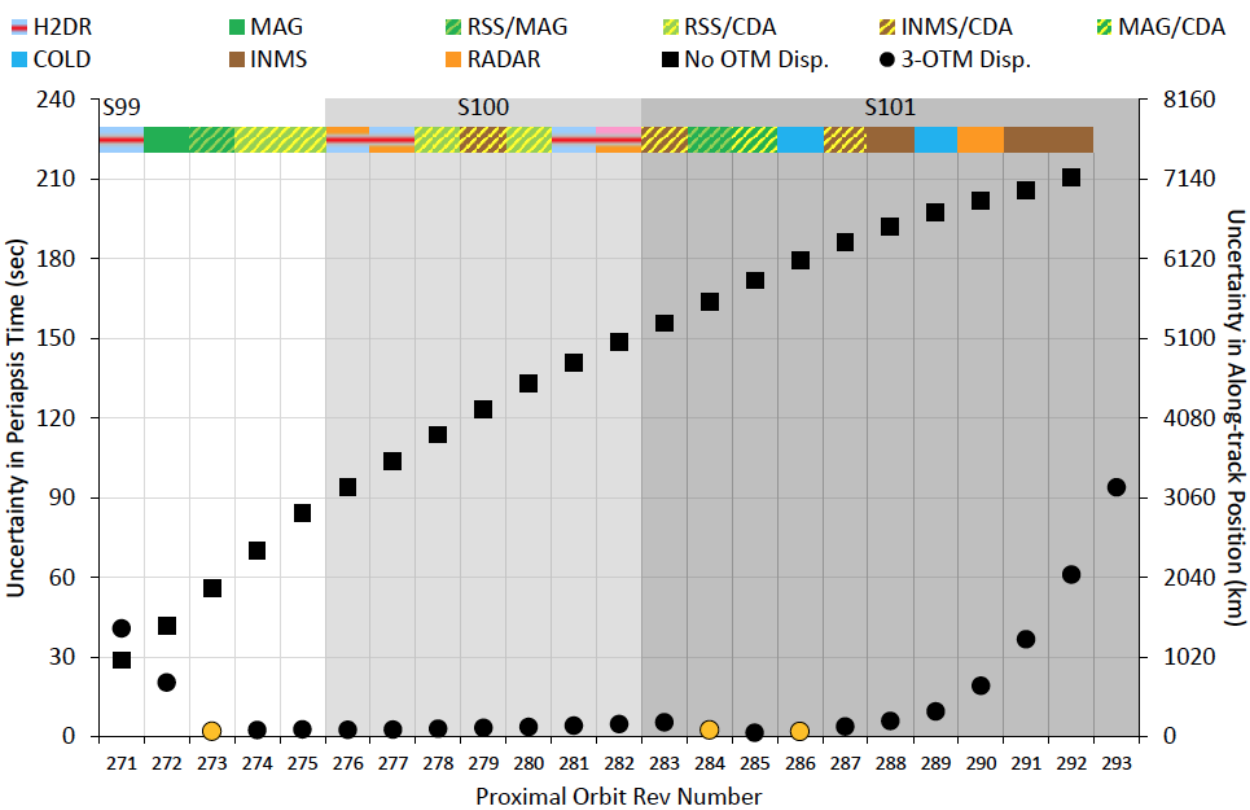
-building 10 week sequences as 2 parts and updating vectors in the second half with a new OD. This was incompatible with current memory management tools

-build a 10 week sequence as two 5 week sequences. Increased workload on teams was a concern

-introduce additional OTMs to reset position errors (maintain reference trajectory). The delta-V required for these additional maneuvers was not accounted for in initial FRPO planning performed in 2010, but studies in 2014 and continuing resource tracking indicate this will be possible with >99% certainty of not running out of all propellant sources (there is a 6.5% chance we will run out of bipropellant, but the added maneuvers are small enough to be performed with hydrazine). Three additional OTMs have been planned for, which reduce periapse timing uncertainties to the lower curve in figure 7 (note this figure is 3σ, accounting for the difference from figure 5). This is done by using three chosen proximal periapses as trajectory control points, shown in yellow in figure 7.

The escalating uncertainties from rev 288 thru 293 are a response to Saturn atmospheric uncertainties; in response we decided to create "movable" block programs for those five periapse periods, which would then be updated with ephemeris files created very close to each of these periapsis epochs, without impacting the rest of the background sequence. These activities would shift in time in order to account for this periapsis time shift, thus allowing us to optimize our science activities.

The additional OTMs have reduced the expected live updates to an acceptable level for workforce, and negate the



need for splitting sequences into 2 parts or ingesting late ODs, as we stay on the reference trajectory just as if we had targeted encounters a la prime and extended mission.

Saturn Models

Another challenge encountered was the definition of this ~2900 km corridor between the D-Ring and Saturn's atmosphere. These boundaries are "fuzzy" and in the case of Saturn's atmosphere, are changing with time. With respect to the D-ring, it is not a clear line of demarcation that determines where the dust is no longer a threat to the spacecraft. At the ring plane crossing, the spacecraft velocity will be ~32 km/sec so it will be essential that enough margin be factored in so as to not impact these particles. On the other side of this corridor, it appears that Saturn's atmosphere is now contracting. When this trajectory was originally designed, the atmosphere appeared to display a blooming characteristic. If we get too low within the atmosphere, the spacecraft might be permanently (and prematurely captured), ending the mission. If we don't get close enough to the atmosphere, we will not get the in situ date we are looking to capture with our instrument suite. Contingency plans have been devised and put into place to address both of these conditions.

Dust Hazards- The Cassini mission planning team has always analyzed each trajectory for any "dust hazards", times where our trajectory could cause an impact on a sensitive instrument or spacecraft body part that could cause damage [3]. The spacecraft has flown these periods of time with its high-gain antenna pointing in the direction of the possible dust flux, known as HGA to RAM (HGA2RAM). Both the F-ring orbits and the proximal orbits pass near known dusty regions. During 2012-2015 images of the faint rings were taken in an effort to constrain the size distributions of the particles in them. The F-ring orbits were determined to not require any HGA2RAM protection periods. The first proximal orbit is planned for a safe distance away from the edge of the D-ring, however this is an unexplored area and concern remains about the particle flux in this region. The first proximal periapse (rev 271), and the 4 above the 64000 km range to Saturn (see figure 4), have been planned with HGA2RAM during the ring plane crossing (RPX). The data from the Radio and Plasma Wave Science (RPWS) instrument during the rev 271 RPX will be used to determine if the sub-64000 km corridor is dustier than expected; if so, commands will have been pre-built to fly each following RPX as HGA2RAM as well, instead of the desired science attitude. (Note, the Cosmic Dust Analyzer (CDA) instrument's field-of-view is hidden behind the antenna during HGA2RAM. Several calibration activities were performed to cross-correlate RPWS results with CDA results.)

Atmosphere Density- After the T126 Titan flyby on 04/22/16, Cassini's trajectory will be such that it will fly 22 orbits between the inner-most D-Ring and the top of Saturn's atmosphere, prior to its impact into Saturn. Figure 4 illustrates how close to Saturn's atmosphere the spacecraft is planned to fly during the last 5 orbits. The periapsis altitude for the last 5 orbits were specifically designed so that we could collect in situ data, primarily from the INMS instrument. The INMS instrument would like to go as low as reasonably possible. Our planned ballistic trajectory factored this in and was released in September 2015. However recent occultation observations seem to indicate that Saturn's atmosphere is contracting, and may result in INMS not being able to "sniff" the atmosphere, which is one of the primary science objectives of the mission during the proximal orbits.

As a result, contingency plans are being put in place [4]. After rev 290, if we determine that the atmosphere has continued to contract, and assuming we have sufficient propellant reserves, we are entertaining performing a spacecraft maneuver that will lower all subsequent periapsis attitudes (figure 8). Preliminary analysis has indicated that performing a 4 m/sec maneuver would lower the periapsis altitude by ~300 km and decrease the orbital period by ~3 minutes. This would satisfy the INMS desire to dip into the atmosphere. The timing shift would be accommodated via our existing plans to execute the periapsis science activities via movable block updates, as described above.

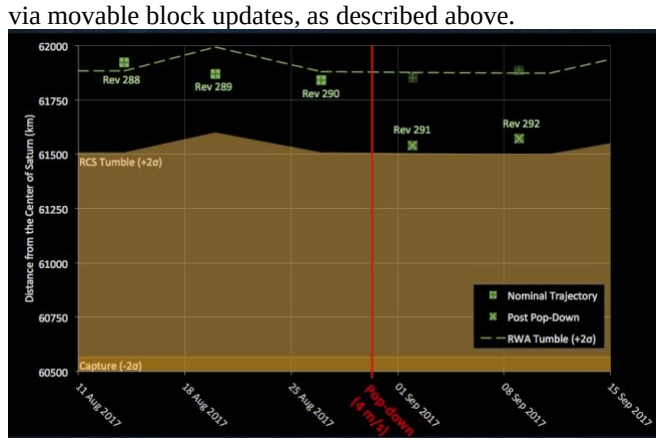


Figure 8. Pop-down maneuver effect

Conversely, if the atmosphere appears to be blooming, contingency responses may need to be put into place to raise the periapsis altitude. In this scenario, there are actually two responses being considered, the first being to change the fly-by altitude using a "low-torque" altitude. This approach has been successfully used in the past for low altitude Titan flybys. This option would not require any propulsive maneuver, but simply overlay the pointing design in the background sequence with the "low-torque" attitude. We could also employ the strategy mentioned above in order to execute a propulsive maneuver to raise the altitude in order to counter the effects of the blooming atmosphere.

Heating

Another challenge of the FRPO orbits was the close proximity to the giant planet causing increased heating to sensitive instruments such as the Composite InfraRed

Spectrometer (CIRS) and the Visible and Infrared Mapping Spectrometer (VIMS). Both of these instruments have flight rules pertaining to both the number of large heating events (health and safety flight rule), and also the acceptable temperature while the instrument is taking data (operational flight rule). However the heating models for each instrument in the pointing design tool (PDT), used by instruments to design their observations, needed to be updated to accurately model the Saturn heat flux at close distances. An updated thermal model was developed for the CIRS instrument to account for this new environment. Due to the length of the Cassini mission and the loss of corporate knowledge with the original instrument developers, we were able to utilize the updated thermal model made for the CIRS instrument and incorporate an equivalent model for the VIMS instrument.

The Science Observation Design (SOD) working group was formed in 2012 to begin early designs of likely FRPO science to look for excessive heating, and uncover any other tool deficiencies like the heating models. The desired science-acquisition attitude for some instruments, such as INMS, was shown early on to cause large heating events for both CIRS and VIMS. When INMS took data at periapse, there could be no subsequent CIRS or VIMS observations for many hours until those instrument cooled down. In 2014 a proximal exercise was performed, in which each of the discipline-focused target working teams fully integrated and implemented in PDT a representative proximal periapse period. In addition to being hampered by the lack of updated heating models, an inaccuracy in the high-gain antenna modeling in PDT was uncovered. Lessons learned from the exercise were included in updated Integration Guidelines and Constraints, such as requiring PDT designs during integration for most periapse periods, and working star-ID bright body issues during integration.

Final Plunge

As the spacecraft plummets into Saturn's atmosphere, we want to get the last bit of science data we can prior to losing control authority as the spacecraft can no longer compensate from the torque being applied by the atmosphere. Unfortunately, Cassini does not have any capability of sending science data back in real-time. As a result, a strategy needed to be put in place in order to downlink science data as close to real-time as possible [5]. The downlink data rate will be flatlined at a rate supportable by both a 34 meter and 70 meter antenna to account for potential DSN antenna problems, with both antennas being scheduled to ensure capture of this extremely valuable end of mission science data set. The instrument data rates will be set such that their data will be written to the solid-state recorder at just below the playback rate, so that the onboard computer will process the data written to the SSR and place it in the downlink stream nearly instantaneously. In this way the INMS instrument, and other in-situ instruments, can send back data until control authority of the spacecraft is lost and tumbling takes the high-gain antenna off of earth point.

Contention for periapse time

At the Cassini Project Science Group (PSG) meeting #58, held in October 2012, each of the science disciplines gave initial input on how much time they needed (relative to periapse) to meet their science objectives, for both the F-ring and proximal phases. A Grand Finale Sharing Working Group (GFSWG) was formed in 2013 to determine which instruments could share periapse periods (either through simultaneous data taking or adjacent observations) in response to the obvious oversubscription of periapse time.
At PSG #63 in June 2014, there was a final submission of discipline requirements for periapse time. A small group was formed to try to come up with periapse time allocations for proximal orbits that met everyone's desires, but it quickly became apparent that negotiations would be required to come up with a compromise solution. The Proximal Orbit Science Team (POST) was formed in late August 2014, to iterate on possible periapse allocations. The first draft allocations were presented at PSG #64 in October 2014, and after more negotiations were subsequently agreed on at PSG #65 in January 2015, pending a few preliminary designs to verify the amount of heating was acceptable. Once that work was done the final POST allocations were set, as seen in Figure 9.

Even as the POST was finishing up their work, the next step in the process needed to be defined to keep on schedule. For the Cassini extended and solstice mission, a process was used to pre-allocate set blocks of time, known as Pre-Integrated Events (PIEs) [6]. The PIE process used for the Solstice mission was updated in late 2014 to account for how POST pre-allocations would be accounted for, and to come up with a new simultaneous segmentation/PIE process. This group had a tight schedule to make sure the disciplines could start integration in time to be ready for implementation of the first F-ring sequence in 2016. PIE inputs were due from the disciplines in January 2015, with PIE negotiations occurring between February and May 2015. The results were presented at PSG #66 in June 2015, and agreed to by all (figure 10).

Rev	271	272	273	274	275	276	277	278	279	280	281
	Intermediate Altitude Periapses (~63,000 km)					High Altitude Periapses (~64,000 km)					
RCS control at periapse		RCS 3:08									
Sequence	S100	S100	S100	S100	S100	S100	S100	S100	S100	S100	S100
Segment owner	Saturn	XD	Maps	Rings	Saturn	Rings	Rings	Saturn	Maps	XD	Saturn
peri-12 to -6 hrs			RSS	RSS	RSS			RSS		RSS	
peri -6 to -5 hrs			RSS	RSS	RSS			RSS		RSS	
peri -5 to -4 hrs		MAG	RSS/MAG	RSS	RSS			RSS		RSS	
peri -4 to -3 hrs		MAG	RSS/MAG	RSS	RSS			RSS		RSS	
peri -3 to -2 hrs		MAG	RSS/MAG	RSS	RSS			RSS		RSS	
peri -2 to -1 hrs	CIRS N Pol	MAG	RSS/MAG	RSS	RSS	RADAR Rings	ISS Rings	RSS		RSS	ISS Saturn
peri-60 to-45 min	ISS Saturn	MAG	RSS/MAG	RSS/CDA	RSS/CDA	RADAR Rings	ISS Rings	RSS/CDA	INMS/CDA	RSS/CDA	ISS Saturn
peri -45 to-30 min	ISS Saturn	MAG	RSS/MAG	RSS/CDA	RSS/CDA	RADAR Rings	ISS Rings	RSS/CDA	INMS/CDA	RSS/CDA	ISS Saturn
peri-30 to-10 min	Slew*	MAG	RSS/MAG	RSS/CDA	RSS/CDA	Slew	Slew	RSS/CDA	INMS/CDA	RSS/CDA	Slew*
peri-10 to -0 min	HGA to RAM*	MAG	RSS/MAG	RSS/CDA	RSS/CDA	HGA to RAM	HGA to RAM	RSS/CDA	INMS/CDA	RSS/CDA	HGA to RAM*
peri 0 to +10 min	HGA to RAM*	MAG	RSS/MAG	RSS/CDA	RSS/CDA	HGA to RAM	HGA to RAM	RSS/CDA	INMS/CDA	RSS/CDA	HGA to RAM*
peri+10 to+30 min	Slew*	MAG	RSS/MAG	RSS/CDA	RSS/CDA	Slew	Slew	RSS/CDA	INMS/CDA	RSS/CDA	Slew*
peri+30 to +45min	ISS Saturn	MAG	RSS/MAG	RSS/CDA	RSS/CDA	ISS Rings	RADAR Rings	RSS/CDA	INMS/CDA	RSS/CDA	ISS Saturn
peri +45 to +60 min	ISS Saturn	MAG	RSS/MAG	RSS/CDA	RSS/CDA	ISS Rings	RADAR Rings	RSS/CDA	INMS/CDA	RSS/CDA	ISS Saturn
peri+1 to +2 hrs	CIRS S Pol	MAG	RSS/MAG	RSS	RSS	ISS Rings	RADAR Rings	RSS		RSS	CIRS S Pol
peri+2 to +3 hrs		MAG	RSS/MAG	RSS	RSS			RSS		RSS	
peri+3 to +4 hrs		MAG	RSS/MAG	RSS	RSS			RSS		RSS	
peri+4 to +5 hrs		MAG	RSS/MAG	RSS	RSS			RSS		RSS	
peri+5 to +7 hrs			RSS	RSS	RSS			RSS		RSS	
peri+7 to +12 hrs			RSS	RSS	RSS			RSS		RSS	

Rev	282	283	284	285	286	287	288	289	290	291	292
	Intermediate Altitude Periapses (~63,000 km)					Low Altitude Periapses (62,000 km)					
RCS control at periapse				RCS 3:55			RCS 2:17	RCS 2:10	RCS 3:19	RCS 2:15	RCS 2:15
Sequence	S100	S101	S101	S101	S101	S101	S101	S101	S101	S101	S101
Segment owner	Rings	Rings	Saturn	Maps	SOST	Maps	Saturn	Maps	Saturn	Saturn	Saturn
peri-12 to -6 hrs			RSS								
peri -6 to -5 hrs			RSS								
peri -5 to -4 hrs			RSS/MAG	MAG							
peri -4 to -3 hrs			RSS/MAG	MAG							
peri -3 to -2 hrs			RSS/MAG	MAG							
peri -2 to -1 hrs	UVIS Rings		RSS/MAG	MAG					RCS xtion		
peri-60 to-45 min	UVIS Rings	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	AUR INB	RADAR Saturn	INMS**	INMS***
peri -45 to-30 min	UVIS Rings	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	COLD	RADAR Saturn	INMS**	INMS***
peri-30 to-10 min	Slew	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	COLD	RADAR/INMS	INMS**	INMS***
peri-10 to -0 min	HGA to RAM	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	COLD	RADAR/INMS	INMS**	INMS***
peri 0 to +10 min	HGA to RAM	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	COLD	RADAR/INMS	INMS**	INMS***
peri+10 to+30 min	Slew	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	CIRS S Pol	RADAR/INMS	INMS**	INMS***
peri+30 to +45min	RADAR Rings	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	CIRS S Pol	RADAR Saturn	INMS**	INMS***
peri +45 to +60 min	RADAR Rings	INMS/CDA	RSS/MAG	MAG	COLD AUR	INMS/CDA	INMS/CDA*	CIRS S Pol	RADAR Saturn	INMS**	INMS***
peri+1 to +2 hrs	RADAR Rings		RSS/MAG	MAG	COLD AUR		RCS xtion		RCS xtion	RCS xtion	RCS xtion
peri+2 to +3 hrs			RSS/MAG	MAG	COLD AUR/ENC						
peri+3 to +4 hrs			RSS/MAG	MAG	COLD ENC						
peri+4 to +5 hrs			RSS/MAG	MAG	COLD ENC						
peri+5 to +7 hrs			RSS		COLD ENC						
peri+7 to +12 hrs			RSS								

Figure 9. POST allocations

PIE Hours received (original total avail: 115):

	Total	Fring	Proximal
Icy	157.7	80.1	77.6
MAPS	140.7	77.4	63.3
Rings	124.2	72.2	52
Saturn	127	44	83
Titan	165.1	67	98.1

	Total Integration Days		Segments	Periapses
Icy	11.5	4%	3	2
Maps	49	17%	11	11
Rings	68.25	24%	13	13
Saturn	83.5	29%	15	12
Titan	26.25	9%	13	0
XD	50.25	17%	9	4
	289.75		65	42

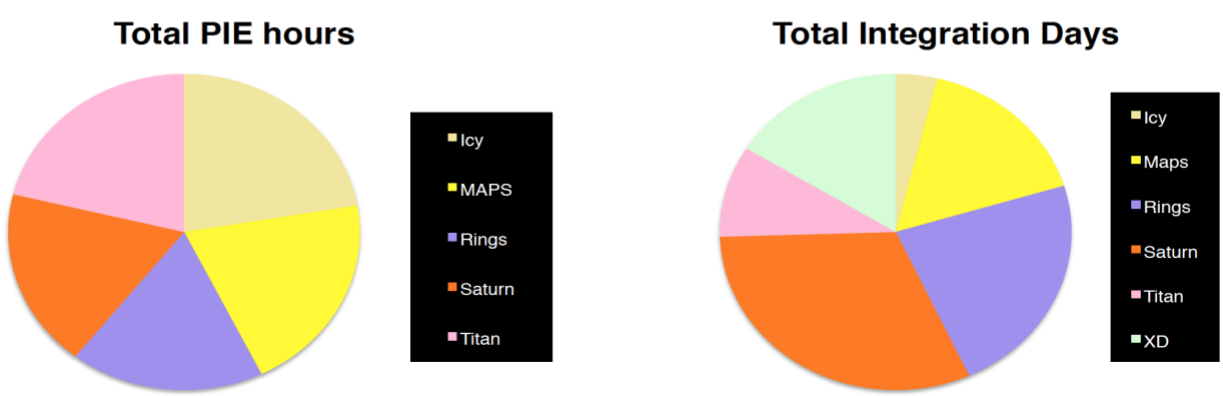


Figure 10. PIE and segmentation results for FRPO per discipline

Workload challenges

The final piece to the puzzle required for integration to begin was to update the integration guidelines and constraints (G&C). Most of the changes were in response to the perceived workload challenges posed by the FRPO trajectory.

-The sequence development process was examined and more time given to observation design, in preparation for these science-dense periods

-Any period which involved custom handoffs from one science design to the next were required to be pre-designed in PDT. This not only flushed out complexities in the toughest designs early, but also reduced the workload in advance of a sequence delivery date

-The reaction-wheel bias optimization tool (RBOT) constrained the amount of time spent at low wheel speed rates, and assumed reaction wheel biasing activities were executed over downlink periods; for F-ring we asked teams to provide windows during the periapse observation period to assist RBOT in placing biases without requiring changes to science designs, and in proximal we will allow more time to occur in this low wheel speed region.

-Science teams prioritized their observations and the highest value time periods were pre-planned to be played back twice, a process almost impossible to do in response to real-time downlink anomalies. During the Solstice mission a handful of these dual playbacks were performed, mostly for targeted flybys; in the F-ring orbits, several were added for non-targeted best-ever small icy rock flybys and close ring observations; in proximal, every periapse not devoted to gravity science contains a dual playback of one or more observations

-Analysis of the actual data utilization over the course of the mission allowed us to model data compression more accurately. As a result we are able to have more downlink margin and flexibility during negotiations for antenna downlink time

The early delivery of PDT designs allowed the spacecraft team, and in particular the Attitude Articulation Control Subystem (AACS) to look at early RBOT solutions. About half a dozen full downlink to downlink segments were integrated and designed. Mission experience to date had suggested that the day of periapsis would be surrounded by reaction-wheel biases to optimize the RWA wheel speeds for the challenging pointing of F-ring and proximal science designs. In 7 of the 22 proximal orbits the spacecraft will use thrusters for attitude control rather than the wheels, required for higher turn rates that can not be achieved with the reaction wheels. Additionally, it was found that the proximal orbits where Radio Science is prime (6 of the 22 orbits) are also extremely easy solutions. Finally, because of the challenging geometries, the science teams were inserting a quiescent period to allow the stellar reference units to reacquire known stars in their field of view. These quiescent periods can also be used to rebias the reaction wheels. In light of these three key findings the spacecraft team updated their reaction-wheel bias strategy, allowing the use of additional off-Earth bias, instead of asking science teams to tweak their observation designs.

The updated G&C were published in late July 2015. The first F-ring segments were delivered in June 2016.

4. CONCLUSIONS

Current Status

As of October 2016 all the F-ring segments have been delivered, and the first F-ring sequence (S97) is in its final stages of development. In December we will begin executing the F-Ring orbits. In late February 2017 we will have completed 13 of the 20 F-ring periapses, and have delivered all the segments for the proximal orbits. The final 3 sequences (S99, S100, and S101) will be in various stages of development. On April 26 we will begin execution of the proximal orbits; the end of mission is September 15, 2017.

Sequence development has followed the revised Guidelines and Constraints, semi-relaxed RBOT and data volume management rules, and incorporated the new heating models. In S97 18% of science designs were completed before sequence development; in S98, 36%, S99/S100/S101 TBD. There were many more consumable level heating events for the VIMS instrument than usual. More off-earth biases were used to solve RBOT problems, using more hydrazine than expected.

Lessons Learned

Advanced Planning- The advance planning performed, starting more than 4 years before the FRPO orbits began, were crucial in allowing the existing science, planning, and spacecraft teams to fly a complex spacecraft, plan and develop the end of the Solstice mission, while simultaneously performing analysis and development work to fly a brand new mission with aging hardware.

Jumpstarts in the Cassini planning process are times when we look ahead at an entire set of opportunities and try to achieve the best balance of overall science by working the trades across the entire set of opportunities at once, rather than in piecemeal fashion. This has worked for Cassini in the past (Titan flybys, PIEs for Solstice Mission), and it was something that was expanded on and worked well in FRPO. The POST and S/PIE groups tackled the challenges early and allowed the technical teams to work tricky issues (heating, RBOT guidelines, pointing uncertainty tolerances, the need for HGA contingency process or pop-down, etc.)

The early SOD, sharing working group, and exercise flushed out many of main issues, like the heating for almost any science pointing at periapsis. Process changes, like the early PDT designs allowed teams to meet ambitious

delivery schedules for sequence development for S97 and S98 while complicated segment integration was ongoing. Having teams include quiescent periods in periapse designs allowed the attitude control team to find RBOT solutions without requiring much loss of precious science

Build in flexibility and the ability to react as late as possible to issues - Identifying model uncertainties (Saturn's atmosphere and D-Ring dust) allowed the project technical teams to create plans that optimized science yet provide contingency options should the need arise in order to react if the atmosphere or dust density environments proved to be worse than predicted by the models. The cross calibration done with RPWS and CDA during the dust crossing in the F-ring orbits, will allow RPWS to provide data during the first proximal orbit dust crossing, allowing the project to decide to continue with the planned science observations or to invoke the HGA to Dust Ram contingency plan in order to protect the spacecraft, if the environment is deemed too hazardous. Similarly, the first passage through Saturn's atmosphere in Rev 288 will obtain the data necessary for the Saturn team to update the atmospheric model, allowing for an opportunity to perform a pop-down maneuver (or pop-up if needed) in order to optimize the in-situ science of Saturn's atmosphere (one of the top 3 science objectives).

Expect a changing risk posture - The Cassini PRIME, Equinox, and Solstice Missions have been tremendously successful. When the F-Ring and Proximal Orbit Mission was proposed it was understood that we were taking the spacecraft to a location where it was never designed to go. The science opportunities were compelling enough to warrant this mission, and the project science, planning, navigation, and spacecraft team all rallied to think outside the box of how they had been running the spacecraft for a decade. Everyone and every team has been nimble and aggressive. This was allowed by a risk posture change at the Project, Program and Headquarters level. Without that change in risk posture and support from all levels of management to try the hard things we would never be in a position to achieve such amazing science and end the mission in blaze of glory.

Results

For the January final paper due date I will include some initial F-ring images, and the TBDs above will be filled in.

APPENDICES

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BIOGRAPHY

Nancy Vandermey *received a B.S. in Mechanical Engineering from Michigan Technological University in 1989, and a M.S. in Engineering Mechanics from Virginia Polytechnic University in 1991. She has been with JPL since 1996, serving as a systems engineer on the Galileo mission to Jupiter and a science planning engineer on the Cassini mission to Saturn..*

William Heventhal III *received a B.S. in Electrical Engineering from San Diego State University in 1986. He has been with JPL since 1989, serving as a Mission Controller on the Magellan mission, Software Engineer for the Mars Pathfinder, Mars Observer, and Cassini missions, and is currently the Science Planning and Sequencing Team Manager for Cassini.*

Trina Ray *has been working on the Cassini Mission since before launch as an instrument operations lead for the Radio Science Team, as part of the Science Planning Team supporting Titan integration and sequence development, as the Project Science System Engineer, and currently as the Titan Orbiter Science Team (TOST) co-chair and the Science Planning and Sequencing Deputy. She has a MS in Astronomy from San Diego State University and a BS in Physics, Astronomy option from CSUN.*