The Last Orbit: Planning Cassini's Plummet into Saturn

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Cassini's final orbit around Saturn will culminate in a dramatic ending as the spacecraft plunges into the ringed planet's atmosphere, never to escape or be heard from again. The last hours of the mission prior to the final loss of signal have some of the most unique and valuable science to date. Cassini will take a unique trajectory to dive deep into the atmosphere on its approach to final disposal and no spacecraft, Cassini included, has entered these depths of Saturn's atmosphere. The science community has placed heavy emphasis on this once-in-a-lifetime opportunity to inspect these deeper regions of Saturn's atmosphere. The Cassini project specifically aims to collect the very last bits of data during the final plunge to get samples of the deepest regions before the spacecraft is lost forever. The desire to collect the final bits of data presents several challenges. Cassini's Mission Planning (MP) team has developed an End of Mission (EOM) scenario to tackle these demands. The EOM scenario outlines the framework for the entire last orbit of the mission and details the strategy for data collection and transmission. Attaining near real-time transmission is key for the acquisition of the very last bits of data. The Cassini spacecraft will use a new mode of operations to successfully achieve this real-time transmission. In addition to this primary investigation and planning for telecommunications, key risks have been studied within the realm of the last orbit. Ultimately, this paper shows how the Cassini Project plans to ensure the return of every last bit of data before the spacecraft is consumed by Saturn forever.

Nomenclature

MP	=	Mission Planning
EOM	=	End of Mission
RTG	=	Radioisotope Thermoelectric Generator
CDS	=	Command and Data System
SSR	=	Solid State Recorder
DST	=	Deep Space Transponder
TWTA	=	Traveling Wave Tube Amplifier
AACS	=	Attitude and Articulation Control Subsystem
RCS	=	Reaction Control System
RWA	=	Reaction Wheel Assembly
MEA	=	Main Engine Assembly
SFP	=	System Fault Protection
CDA	=	Cosmic Dust Analyzer
CIRS	=	Composite Infrared Spectrometer
INMS	=	Ion and Neutral Mass Spectrometer
MAG	=	Magnetometer
MIMI	=	Magnetospheric Imaging Instrument
RPWS	=	Radio and Plasma Wave Science
UVIS	=	Ultraviolet Imaging Spectrograph
CAPS	=	Cassini Plasma Spectrometer
ISS	=	Imaging Science Subsystem

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RADAR = Cassini Radio Detection and Ranging
VIMS = Visible and Infrared Mapping Spectrometer
S101 = Sequence 101
DSN = Deep Space Network
OTM = Orbit Trim Maneuver
Rev = Revolution
LOS = Loss of Signal
SCET = Spacecraft Event Time
T126 = Titan Flyby 126, the last targeted Titan flyby
kbps = kilobits per second
DSS = Deep Space Station
70-m = 70-meter DSN antenna
34-m = 34-meter DSN antenna
DOY = Day of Year
SP = Science Planning
UTC = Coordinated Universal Time
FSDS = Flight Software Development System
SCO = Spacecraft Operations

I. Introduction

Cassini's days are numbered. On September 15th, 2017, the spacecraft's 13-year tour around Saturn will come to an end. Cassini launched in 1997 and arrived at Saturn in 2004. Its prime mission lasted four years, and its first mission extension, the Equinox mission, lasted from 2008 to 2010. Cassini is currently flying its Solstice Mission—the second and final mission extension that will conclude with spacecraft disposal into Saturn[2]. The Solstice Mission lasts seven years and involves periods of equatorial orbits, inclined orbits and the final "proximal orbit" phase during which the spacecraft will make numerous passes through the innermost ring of Saturn and Saturn's upper atmosphere. This proximal orbit phase spans from April 2017 to September 2017, and it contains several Saturn atmospheric transits[1]. The final mission-ending descent into Saturn, however, has the spacecraft's deepest atmospheric dive yet. Science data during this final plunge gets more and more precious the deeper the spacecraft descends. The primary goal during the end of the mission is to obtain the very last bits of data, representing the deepest regions of Saturn, sent from the spacecraft just before the signal is lost forever. In order to plan and perform this feat, an End of Mission (EOM) scenario has been developed to capture and organize all necessary objectives, spacecraft states and events during this crucial time period.

A. Cassini Spacecraft

Cassini, shown in Figure 1, is a 3-axis stabilized spacecraft powered by three radioisotope thermoelectric generators (RTGs). Its Command and Data System (CDS) contains redundant computers, CDS-A and CDS-B, and redundant Solid State Recorders (SSRs) A and B. The spacecraft is currently configured with CDS-B prime and CDS-A in hot backup, and this configuration will nominally be in place during the EOM scenario. The Telecom subsystem has a high-gain and low-gain antenna. The high-gain antenna is used for two-way transmission. The normal configuration contains Deep Space Transponder (DST)-A and Traveling Tube Wave Amplifier (TWTA)-B, cross-strapped for polarization. The Attitude and Articulation Control Subsystem (AACS) has both a Reaction Control System (RCS) with thrusters and Reaction Wheel Assemblies (RWAs) for pointing control. The Propulsion Subsystem also contains a Main Engine Assembly (MEA) for large maneuvers, but this is not used in this scenario. There are no maneuvers during the last orbit of the mission. This scenario uses the RWAs for science observations, but will switch to RCS thrusters during atmospheric transits and the final descent into

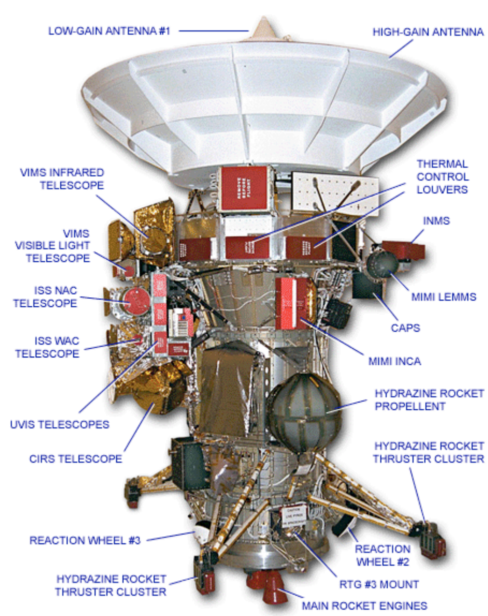

Figure 1. The Cassini Spacecraft[3].

Saturn. System Fault Protection (SFP) contains monitors and devices to respond to faults or invoke safing as needed. The spacecraft also contains thermal devices to control the thermal state of the spacecraft.

In addition to these engineering subsystems, Cassini has 12 science instruments. The following science instruments are in this scenario: Cosmic Dust Analyzer (CDA), Composite Infrared Spectrometer (CIRS), Ion and Neutral Mass Spectrometer (INMS), Magnetometer (MAG), Magnetospheric Imaging Instrument (MIMI), Radio and Plasma Wave Science (RPWS), and Ultraviolet Imaging Spectrograph (UVIS). Cassini Plasma Spectrometer (CAPS) is currently off due to an anomaly and will stay off for the EOM. Imaging Science Subsystem (ISS), Cassini Radio Detection and Ranging (RADAR) and Visible and Infrared Mapping Spectrometer (VIMS) are not used in this scenario.

B. Normal Spacecraft Operations

Cassini operates based on a combination of lengthy pre-planned background sequences and other, more rapidly designed, real-time commands. The final orbit of the mission, including the final descent, is contained within Sequence 101 (S101), the last sequence of the mission. Cassini sequences normally have a 20-week development cycle. This cycle includes the design of science observation periods, the planning and placement of engineering activities, and Deep Space Network (DSN) resource negotiations. These sequences are denoted as the "background sequence" and typically operate on the spacecraft for 10 weeks. The background sequence contains all planned science observations, necessary operational mode changes, periodic engineering activities and any other activities that do not require real-time, or close to real-time, design and execution. Certain periods of time, however, are used for real-time activities within the background sequence. Some examples of real-time activities are live pointing updates for flybys, Orbit Trim Maneuvers (OTMs) and science instrument flight software updates or responses to science instrument anomalies. These activities are designed and performed in real-time (or close to real-time) because they require the latest data for proper design, or, in the case of anomalies, they occur suddenly and necessitate immediate response by the spacecraft teams.

After the real-time activity is designed, the commands are uplinked over a specified communication opportunity, called a DSN pass. Light time is an important consideration during these activities. One-way light time from Earth to Saturn is approximately 1.5 hours. The Cassini team on the ground can, therefore, check the receipt of real-time commands on the spacecraft round-trip light time later, or three hours after the commands are sent. The final orbit of the mission is contained within S101 and all science observations and activities, including the final descent into Saturn, will be included in the S101 background sequence. Even though the final descent is included as part of the background sequence, it will also be developed as a separate real-time mini-sequence should an anomaly arise near the end of the mission. This mini-sequence can be uplinked to establish the correct EOM states on the spacecraft for the final descent. (See Section VI for more information on risks and mitigations.)

II. Definition of the End of Mission Scenario

The EOM scenario takes place during the last orbit of Cassini's mission—Revolution 292 periapsis to Rev. 293 periapsis. This final orbit is displayed in Figure 2 on the following page. DSN communication passes are shown in blue. The scenario begins with the start of the DSN pass on September 9th. The figure also shows the last non-targeted Titan flyby, 292Ti, which sets up the final plunge of the spacecraft into Saturn. The last ~14.5 hours of the scenario will have continuous, dual-antenna coverage. The last ~3.5 hours in orange designates the period of "real-time" downlink, which will be discussed in the following sections. This scenario, and the Cassini mission as a whole, ends when the DSN station loses communication signal with the spacecraft. Loss of signal (LOS) occurs when Cassini's RCS thrusters can no longer hold the spacecraft on Earth-point inside Saturn's atmosphere. (Refer to Table 2 for the exact timing of the loss of signal and the RCS duty cycles leading up to this.) The spacecraft begins tumbling when the thrusters lose pointing control. Spacecraft tumbling is shown in red in Figure 2 after the loss of signal. Data can no longer be sent back to Earth once this occurs, and this marks the end of the Cassini Mission.

A. Objectives and Requirements

The primary objective of this scenario is to ensure the successful collection of the unique science data during the final descent up until the LOS. The spacecraft will dive deep into Saturn's atmosphere, and key science instruments will collect data in this unexplored environment. The Ion and Neutral Mass Spectrometer (INMS) will take direct measurements of atmospheric composition and the fields and particles instruments will make their own in situ environment measurements. This data is extremely valuable and the EOM scenario details the plan to secure every last bit of data leading up to the LOS.

There is only one strict requirement pertaining to this segment of time—spacecraft disposal for planetary protection[4]. This requirement will be achieved regardless of the science data collected during the final descent. The last targeted flyby of Titan (T126) will put the spacecraft on a ballistic impact trajectory with Saturn. T126 occurs on April 22nd, 2017, approximately five months prior to the final descent. This trajectory will ensure that the spacecraft will plummet into Saturn and not escape or later impact protected celestial bodies after the end of the mission. Thus, even if the primary objective of data collection is lost, the requirement for planetary protection will be met.

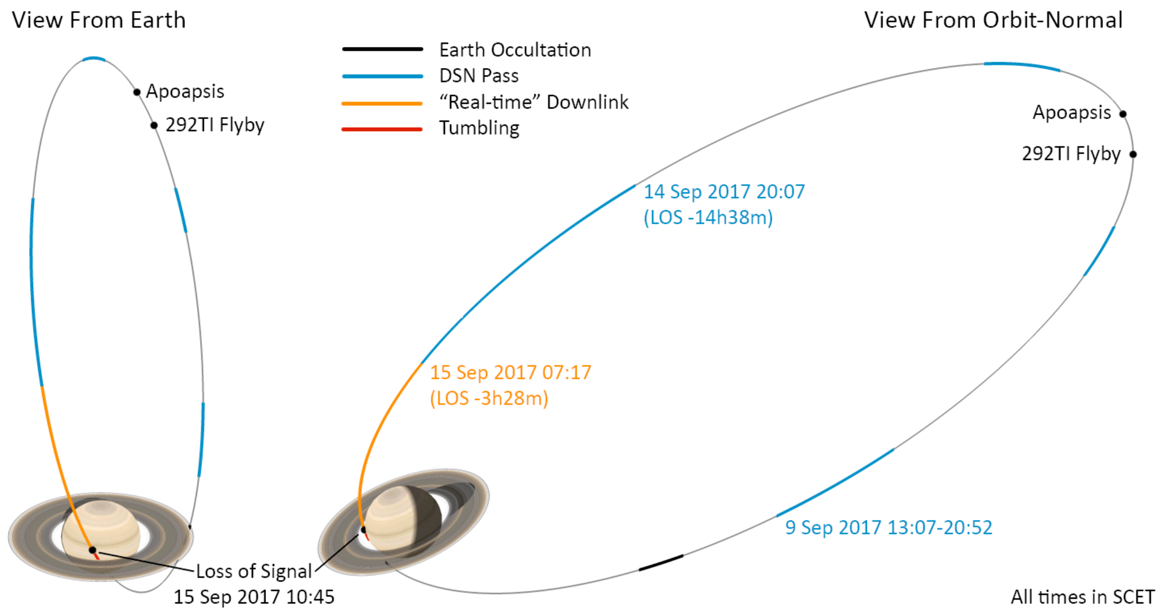

Figure 2. EOM orbit geometry and timeline in Spacecraft Event Time (SCET).

B. Boundary Definitions

The last orbit of Cassini's mission contains four key boundary and transition events. These events mark the beginning of the EOM scenario timeline and the most important points in the data transmission strategy. The four key events are:

1. Beginning of EOM Scenario
2. Continuous Coverage Period
3. Real-time Data Transmission Period
4. End of EOM Scenario

The scenario begins with the start of the first DSN pass after periapsis in Rev. 292. This pass, currently scheduled on September 9th, 2017 as shown in Figure 2, will allow the operations team to determine the health and safety of the spacecraft after the Rev. 292 Saturn atmospheric transit. Operations will be standard from this pass through the majority of the remainder of the final orbit. On September 14th, approximately 14.5 hours prior to the LOS, a period of continuous DSN coverage will begin. This period is used to downlink all of the data on the spacecraft's solid-state recorders (SSRs). This downlink process can take up to 11 hours if the SSRs are completely full. This process may not require the entire allotted time if the SSRs are only partially full and could be started later if further analysis allows. The spacecraft will transition to transmitting data in real-time at 3.5 hours prior to the loss of signal. Specific instrument data collection rates are set to nearly match the spacecraft transmission rate. This allows the data to be transmitted back to Earth in near real-time. The transmission rate was chosen to be 27 kilobits per second (kbps) so that the telemetry rate is supported over a 34-meter Deep Space Station (DSS). (See Section V for more on this decision.) The scenario ends when the DSN antenna loses signal from the spacecraft. Table 1 shows important spacecraft states and transitions for each of the key events.

Table 1. Activity boundary definitions with important spacecraft states.

Event	Spacecraft States and Activites
Beginning of EOM Scenario	• RWA control • Standard operations
Beginning of Continuous Coverage Period	• Assume SSRs are full (though they may not be)
Beginning of Real-Time Data Transmission	• RCS control • SSRs are empty • Instrument collection rates in Table 3 • Spacecraft transmits at 27 kbps
End of EOM Scenario	• Loss of RCS thruster control & loss of signal

III. Guiding Principles

A. Assumptions and Constraints

Several assumptions are made in the EOM scenario. The project is using a specific reference trajectory from September 1st, 2015, along with a Saturn atmospheric model from June 2015. In addition to these specific models, the spacecraft is assumed to be operating nominally during the last orbit. This means that no significant instrument or device failures have occurred and there is sufficient hydrazine to maintain control authority during the atmospheric transits. Subsystem devices, as described in Section I, will be used. (See Section VI for risks and mitigations should any off-nominal states arise in the EOM.) Sequence 101 (S101), the last sequence of the mission which contains the last orbit, will be designed and implemented following the project's normal sequence development schedule. Finally, no new flight software will be developed for this scenario.

Key constraints in this scenario are directly related to data collection and transmission. Transmission rates during the real-time transmission period are constrained by 34-meter antenna rates (27 kbps). The project will request 70-meter coverage for this time period, and 70-m antennas can support higher telemetry rates. The transmission rate, however, must be compatible with a backup 34-meter antenna in the event that the 70-m antenna fails or if a 70-m antenna is unavailable during DSN scheduling. The science instruments must collect data at specific rates that do not exceed the 27 kbps transmission rate in order to achieve the near real-time transmission. These instrument rates are detailed later in Table 3. The project has successfully tested these EOM instrument rates on the spacecraft. Moreover, the duration of the real-time transmission period was decided to be 3.5 hours. (See Section V for this decision.) This 3.5 hour period allows for real-time commands to be sent to the spacecraft should any instruments or devices not behave as expected, such as instrument data collection rates not matching their pre-determined values in Table 3. The operations team can send commands to reinforce or change the states as necessary to affect the last 30 minutes of the mission assuming a three hour round-trip light time. This will ensure that the necessary constraints are met to achieve the real-time data transmission.

B. Operability Considerations

Cassini does not transmit science data in real-time during normal operations outside of this scenario. The spacecraft collects science data during observation periods and stores the data on the SSRs. The spacecraft later turns to Earth-point for a scheduled DSN downlink pass and transmits the data on the SSRs back to Earth. There is not enough time during the EOM scenario to secure the last bits of data using this normal collection and transmission process. This scenario depends specifically on the spacecraft's ability to minimize the latency between data collection and transmission. Data is therefore collected at nearly the same rate it is transmitted. This requires the instrument data production rates to closely match, but not exceed, the downlink data rate.

IV. Event Description & Key Parameters

The last orbit contains several other defining events in addition to those listed in Section II. The following table displays these events in chronological order. The time formats for the events are shown in Spacecraft Event Time (SCET) and time prior to the loss of signal. The SCET format uses the year, the day of the year (DOY), and the hour and minute of that DOY to specify timing. The relative time is shown with the number of days, and additional hours and minutes, the specific event occurs before LOS. The events occur at certain times based on orbit geometry, DSN planning, spacecraft operational constraints or direct Cassini project decision within the context of this scenario. The events in italics are based on project decision and may change based on further evaluation. The start of the real-time transmission period in bold currently affects the timing of all other events in italics. The reason for this will be made apparent in this section.

Table 2. Timeline of events.

Absolute Time (SCET)	Time Relative to LOS	Activity
2017-251T23:04	-006T11:40	Transition to RCS Control
2017-252T01:25	-006T09:19	Transition to RWA Control
2017-252T06:52	-006T03:52	Earth occultation by Rings
2017-252T08:38	-006T02:06	End Earth occultation by Rings
2017-252T13:07	-005T21:37	Beginning of EOM scenario on DSS-63 pass
2017-254T19:03	-003T15:41	Final non-targeted Titan flyby (292Ti)
TBD	TBD	Transition to RCS control for final plunge
2017-257T20:14:31	*-14:30:00*	*Start of continuous coverage*
2017-257T20:14:31	*-14:30:00*	*Turn to Earth & Begin final downlink*
2017-258T07:14:31	*-03:30:00*	*SSRs cleared (latest possible time)*
2017-258T07:14:31	***-03:30:00***	***Start of real-time transmission period***
2017-258T10:43:31	-00:01:00	RCS @ 10% duty cycle
2017-258T10:44:13	-00:00:18	RCS @ 50% duty cycle
2017-258T10:44:28	-00:00:03	RCS @ 90% duty cycle
2017-258T10:44:31	-00:00:00	Loss of signal (RCS @ 100% duty cycle)
2017-258T10:44:31	-00:00:00	End of scenario

Spacecraft pointing control will switch to RCS thrusters just prior to the Rev. 292 atmospheric transit[5]. The spacecraft will return to RWA control after the transit, and RWAs will remain in control for the remainder of the last orbit until the final plunge. Figure 2 and Table 2 show a short Earth occultation by Saturn's rings, six days prior to LOS, due to the geometry of the trajectory. The first DSN pass of the last orbit, which starts on September 9th, will establish the health and safety of the spacecraft following the atmospheric transit. Once the spacecraft status is determined, the remainder of this pass and all other passes in the orbit prior to the continuous coverage period will be used for standard operations and normal science data downlink. The 292Ti non-targeted flyby approximately three days prior to LOS, shown in Figure 2 just before apoapsis, will set up the final plunge of the spacecraft. The most important time period for this scenario, as stated previously, is the last ~14.5 hours prior to the LOS. The exact timing of the spacecraft transition to RCS control has not yet been determined, but will occur somewhere during, or just prior to, this continuous coverage segment. This critical period will have continuous dual DSN antenna coverage, with both 70-meter and 34-meter antennas. During this period, the spacecraft telecommunications subsystem will use the high-gain antenna for two-way communications in X-band. This final region of coverage contains two key segments: 1) ~11 hours to clear full SSRs and 2) near real-time science data transmission once the SSRs are cleared. Currently, the start of continuous coverage directly aligns with the 11 hours it takes to clear the full SSRs and assumes that the real-time transmission period will begin 3.5 hours prior to LOS. The project may decide to start the continuous coverage period earlier, but the duration between the start of this region and the real-time transmission region must be no less that 11 hours for full SSRs. If further evaluation shows that the SSRs will not be full, this assumption will be changed, and the duration can be shortened from 11 hours as necessary.

The near real-time transmission mode required in this scenario enables the spacecraft to return the very last bits of data just before the loss of signal. The project has currently decided to enter this mode approximately 3.5 hours prior to the loss of signal. This timing is, however, not yet finalized. The project may decide to start this transition period as late as one hour prior to the loss of signal. (See Section V for more discussion on this decision and the trade involved.) The spacecraft will transmit at 27,650 bps during the real-time transmission period. Science instruments will be collecting data at the pre-determined rates detailed in Table 3 to achieve the real-time data transmission with the 27kbps rate. The Science Planning (SP) team has determined which of Cassini's instruments will be on for the final descent into Saturn. The science instrument teams have worked with SP to determine their rates for this period.

Table 3. Science instrument data collection rates.

Instrument	Proposed rate (bps)
CAPS	0
CDA	4192
CIRS	1600
INMS	1498
ISS	0
MAG	1976
MIMI	2200
RADAR	0
RPWS	6865
UVIS	1801
VIMS	0

The RCS thrusters will maintain control over pointing as the spacecraft goes deeper into Saturn's atmosphere. Loss of signal will occur when the thrusters can no longer hold the spacecraft on Earth-point due to significant atmospheric torque. LOS is predicted to occur at 2017-258T10:44:31 Spacecraft Event Time (SCET), or September 15th, 2017 at approximately 12:08 UTC (Coordinated Universal Time). The AACS team performed simulations using the Flight Software Development System (FSDS) to predict this time. The simulation used the latest reference trajectory and the latest Saturn atmospheric model to predict the torques placed on the spacecraft by the atmosphere. FSDS also includes a model for the RCS thrusters. The simulation is, therefore, able to predict when the thrusters will no longer be able to hold the spacecraft attitude due to atmospheric torques. The spacecraft will lose RCS control authority, and will no longer be able to maintain an Earth-point attitude, at an atmospheric density of $9x10^{-11}$ kg/m^3 at an altitude of 61,321 km.

V. Decisions, Trades and Analyses

Details of the events during the last orbit, including timing, spacecraft states, DSN planning and other necessary activities, are the result of an on-going decision-making process within the Cassini project. Some decisions involve a minimal trade or analysis and have therefore been finalized. Other decisions that have much more to consider may change in the future. Table 4 displays some important project decisions, their current results and whether or not they are finalized.

Table 4. Key decisions for EOM scenario.

Decision Space	Decision	Finalized?
Spacecraft transmission rate for real-time downlink period	27 kbps	YES
DSN pass coverage for the last orbit	See Figure 2	NO
Station coverage for continuous coverage and real-time downlink	70-m antenna + 34-m antenna	NO
Time to start the real-time transmission period	3.5 hours prior to LOS	NO

The real-time data transmission strategy depends on having a set transmission rate to which the science instrument collection rates can be matched. The project was tasked with first deciding between 70-m rates and 34-m rates for spacecraft transmission. The primary objective of the EOM scenario is to successfully get every bit of data collected at Earth. If 70-m antenna rates were used, a larger amount of data could be sent from the spacecraft, but this rate would not work if the 70-m antenna failed. For this reason, a 27 kbps rate was chosen as it is compatible with both 70-m and the backup 34-m antennas.

The DSN pass coverage for the last orbit, including the final continuous coverage period, has not yet been finalized. Figure 2 shows the planned DSN passes with three passes in the last orbit prior to the final plunge, along with the last continuous coverage pass including the period of real-time downlink. The project may decide to request more DSN passes throughout this last orbit for additional normal science data downlink. The period of continuous coverage prior to LOS may also be extended beyond the 14.5-hour mark. A possible reason to extend this period might be to have more tracking time to view the spacecraft state and to respond to any issues prior to the final descent. The period of continuous coverage also assumes that both a 70-m and 34-m antenna will be used simultaneously. The stations and exact antennas may change upon further evaluation or during DSN negotiations, which will happen during the S101 development process in 2017.

The spacecraft will transmit data in the “real-time” manner as described in Section III during the last hours before the loss of signal. The project’s current decision on the timing of this transmission period is 3.5 hours prior to LOS. The original choice for this timing, however, was only one hour prior to LOS. The SSR clearing period, with this one hour of real-time downlink, would start 13 hours prior to LOS, not 14.5 hours as it is now. This could allow for more normal science data collection in the last orbit leading up to the SSR clearing and the final descent. The one hour was increased to 3.5 hours, however, to allow for real-time responses should the spacecraft not behave as intended. This 3.5 hour period, with a ~3 hour round-trip light time included, gives operators time to send commands to the spacecraft to affect the last 30 minutes of the mission. This is, of course, a trade between more science prior the final descent and adequate time for off-nominal state evaluation and response during the last hours of the mission. This is still an important consideration, and the project may change the real-time transmission period back to one hour.

VI. Key Risks and Mitigations

The spacecraft is assumed to be operating nominally during the last orbit for all of the events described in previous sections. There are, however, some key off-nominal situations that are being investigated: spacecraft anomalies that call spacecraft safing and DSN antenna failures. Other issues could arise in the EOM scenario planning or operation, but these, in particular, are of primary concern in the early planning phase.

A spacecraft anomaly during the last orbit is the most significant risk to the EOM objectives. Major spacecraft anomalies include loss of attitude control (due to RWA or thruster faults), loss of attitude knowledge, a computer or sequencing error, power undervoltage or excessive power draw, and loss of telecom downlink capability (due to transponder or TWTA faults). The spacecraft response to a major anomaly is to enter a known or “safe” state. The safe state objectives are to regain attitude control and to point the spacecraft to Earth for telecommunications. Safing immediately powers the instruments off and stops science data collection and transmission. The spacecraft will command a predictable state, allowing the ground team to respond based on this specific state.

An anomaly leading to spacecraft safing will not compromise the sole requirement for spacecraft disposal. The spacecraft will still be on a ballistic impact trajectory following the T126 flyby, which occurs five months prior to the final descent. An anomaly that calls spacecraft safing during the end of mission, however, could be detrimental to the objective of the unique science data collection. The spacecraft can be recovered from safing, and this data collection process can be salvaged, provided that adequate time is available and safing conditions are not mission-ending. A safing strategy, based heavily on the project’s standard safing strategy, is being developed specifically for this last orbit. The safing response strategy and timeline are not fully detailed at this time, but the high-level responses have been discussed. The response path taken after a safing event during the EOM will depend on the amount of time remaining before key events in the scenario and the criticality of the fault that caused the safing. The possible paths are:

1. Restart the entire S101 background sequence on the spacecraft. This sequence restart includes all of S101, which contains the EOM scenario and the final plunge instrument data collection rates.
2. Uplink a pre-constructed mini-sequence, containing only the final plunge. This is uplinked when there is not enough time to restart the entire background sequence, or the spacecraft fault is such that the project is precluded from restarting the background sequence. This mini-sequence contains the instrument data collection rates during the real-time transmission period and other necessary commands to establish the proper spacecraft state (such as SSR commands should they not be empty) for the final portion of the mission.
3. No response. If there is not enough time to perform responses #1 or #2, the unique EOM science data objective will be lost. The spacecraft will still meet the primary requirement for planetary protection as it will be on a ballistic trajectory into Saturn.

Finally, it is possible that a DSN antenna could fail during any of the passes in the last orbit. This possibility is no different than an antenna failing on any other pass in the mission. The project accepts the data loss with the antenna failure or seeks another antenna immediately depending on the criticality of the pass. The impacts of this risk are much higher during the last 14.5 hours of the mission with the potential loss of the unique science data. The project will request continuous dual-coverage on both 70-meter and 34-meter antennas for this time because of this high impact. The project would immediately request another antenna if the primary and backup antennas were to fail during the last ~14 hours of the mission.

VII. Conclusion

The last orbit of Cassini's mission has been detailed by the project in the form of an End of Mission scenario. This scenario lays out the data collection and transmission strategy such that the latest set of science data is collected and transmitted to Earth during the spacecraft's final descent into Saturn. The primary focus of this scenario is establishing a period of real-time data transmission in the very last hours of the mission. Cassini does not normally transmit data in real-time, so care was taken in developing this strategy. Real-time data transmission involves sending data back to Earth immediately after it is collected by the instruments. Specific instrument data collection rates were detailed to closely match the data transmission rate.

Further framework in this segment has been developed in addition to establishing the details for the transmission. The DSN pass strategy contains continuous dual-coverage for the SSR clearing period and for the real-time transmission period prior to the loss of signal. The DSN coverage leading up to this time has not been negotiated and will continue to be worked as part of the nominal DSN negotiation process. The timing of some events may also change based on further project discussion. The timing for the start of the real-time transmission period involves a trade between more science data collection before this period and more time to respond to issues during the real-time downlink. As stated previously, an anomaly calling spacecraft safing could be detrimental to the data collection in the final descent. The primary safing concepts and response paths have been determined. The Cassini team is, however, still working through the details of the safing strategy, including timing and fault cases. This will provide the team with a clear means to recover the spacecraft in the tight timeline during the EOM. Once all of these details are worked, the project will have a robust strategy in place to collect data as the Cassini spacecraft takes its mission-ending decent into Saturn's atmosphere.

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