Cassini's Grand Finale: A Mission Planning Retrospective

Erick J. Sturm II
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-6449
Erick.J.Sturm@jpl.nasa.gov

Abstract—**On September 15, 2017, Cassini plunged deep into Saturn, down to where the atmosphere was sufficiently dense to destroy the spacecraft, making it part of Saturn forever. In the five months leading up to its destruction, Cassini flew between Saturn and its rings 22 times, collecting data from the never-before-explored region of the Kronian system. These orbits, the Grand Finale of Cassini, were the culmination of years of planning by the Cassini flight team. This paper looks back upon the mission planning effort in particular, comparing the baseline operational scenarios and contingency plans to the as-flown Grand Finale.**

The bulk of the Grand Finale mission planning effort was focused on the environmental hazards present in the region between Saturn and its rings: the dust and the atmosphere. Dust hazard and atmospheric transit contingency plans were in place to help ensure spacecraft health and maximize science data return. The dust hazard plan gave the operations team the option to turn the spacecraft to a safe attitude during ring-plane crossings had the dust environment proved more threatening than anticipated. The atmospheric transit plan would have made use of an orbital trim maneuver in order to raise or lower periapsis depending on the density of the atmosphere.

The proximal environment did have its surprises, though they were good surprises. The dust was significantly less hazardous than predicted. So much so that elements of the contingency plan were leveraged in order to remove a dust hazard protection from the baseline plan, rather than add one to it. While the atmosphere was substantially denser than predicted, it was not dense enough to warrant a periapsis-raise maneuver and actually meant that better in-situ data was gathered. Ultimately, from a mission planning perspective, the Grand Finale went better than expected.

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1. INTRODUCTION

In April 2017, Cassini began its Grand Finale, a series of 22½ orbits that took the spacecraft between Saturn and its rings. The highest four of these orbits flew through D ring dust concentrations high enough to be seen in high-phase images of the region. The lowest five orbits had Cassini flying low enough to take in-situ measurements of Saturn's thermosphere. As such, this final set of orbits provided a unique opportunity to obtain some of the most valuable science data of all the Cassini missions.

Significant work was done in the years leading up to the Grand Finale studying the proximal region, assessing its hazards, and defining contingency plans. The goal was to ensure the spacecraft's health and safety as well as the return of the unique science data from that region. This paper looks back at the baseline operational scenarios and environmental contingencies for Saturn's proximal region and compares them with the actual, as-flown Grand Finale.

Proximal Environment

The proximal environment is the region spanning the gap between the top of Saturn's atmosphere and the bottom edge of the D Ring, shown in Figure 1. The Cassini spacecraft flew through this region 22 times during the Grand Finale.

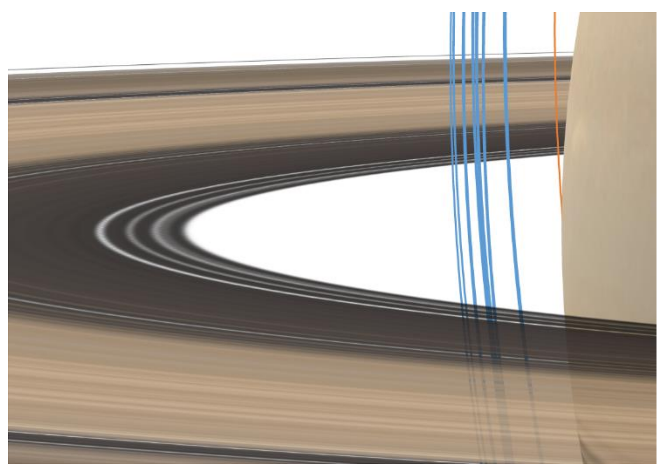

Figure 1: The proximal corridor with the 22 passages (blue) and the impact trajectory (orange)

Flying through this gap meant that each orbit was assuming some amount of risk from the two environmental hazards on either side of the gap: the dust and the atmosphere.

D-Ring Dust—The D ring environment was predicted to be similar to that of the G ring. Remote observations suggested that the D ring brightness at 65,000 km from Saturn's center was comparable in brightness to the core of the G ring. The Cassini spacecraft had flown through the outer fringes of the G ring in the past; however, given the differences in orbital speeds and estimated particle size distributions, equal brightness did not necessarily mean equal dust hazard risk. Analysis of high-phase D ring images was done by Hedman et al to estimate and bound its particle size distribution [1]. Using the results of that work along with the planned spacecraft trajectory and attitudes, the dust hazard risk for each of the proximal orbits was calculated. The highest predicted risks were found to be comparable to those predicted for past G ring crossings [2].

Saturn Atmosphere—Through analysis of ultraviolet solar and stellar occultations of Saturn's atmosphere, D. Strobel and T. Koskinen developed a two-dimensional model of density that varied with radius and latitude [3]. The model provided estimates for the atmospheric densities that the spacecraft would fly through during the proximal orbits. When combined with the planned attitudes of the spacecraft, the Cassini flight-system-dynamics simulator (FSDS) predicted the peak RCS thruster duty-cycles required to fight the atmospheric torque during each transit. The duty cycles were found to be comparable to those of past low-altitude Titan flybys [2]. In addition, the model, the planned attitudes, and the RCS thruster torque capacity combined to define a spacecraft tumble boundary, the radius at which the density was predicted to be sufficient to overwhelm the RCS thrusters and cause the spacecraft to lose control authority.

Proximal Orbits

The proximal orbits, also known as Cassini's Grand Finale, were the final 22½ orbits of the Cassini Solstice Mission, which concluded with the spacecraft permanently entering Saturn's atmosphere. They received their name from their close proximity to Saturn and its rings as their periapsis passages flew between the lower fringes of the D ring and the upper reaches of Saturn's atmosphere. Figure 2 shows Cassini's Grand Finale, which started at apoapsis of Rev 271. After completing 22 full orbits (shown in blue), the spacecraft made the journey from Titan to Saturn one last time (shown in orange). Finally, diving deep into Saturn's atmosphere on Rev 293, it was destroyed.

Even though the Grand Finale consisted of 22½ orbits, it was completed less than five months from its start. The short duration was due to the size of the orbits; with periapsis close to Saturn and apoapsis only slightly outside of Titan's orbit, the period of each orbit was less than one week.

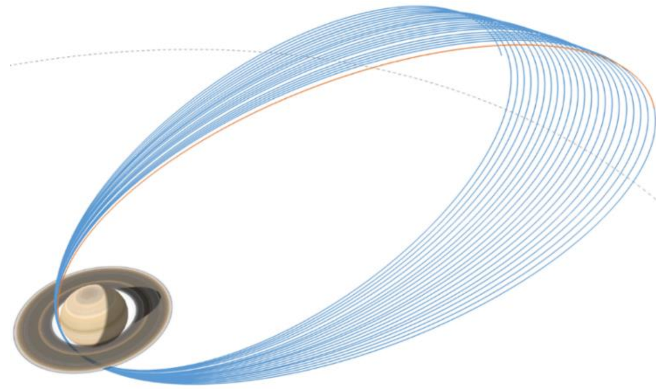

Figure 2. Cassini's Grand Finale with the 22 full proximal orbits in blue, the final half-orbit in orange, and Titan's orbit in gray.

While all the proximal orbits had periapsis passages in the corridor between Saturn's atmosphere and rings, the exact altitudes of the ring plane crossings (RPCs) and periapses varied, as shown in Figure 3. The source of the variation was distant, non-targeted Titan flybys out near the orbits' apoapses, the last of which pulled the trajectory out of the safe corridor down into Saturn. The variation in altitudes caused by these flybys meant that each orbit had a different amount of risk with respect to the D ring dust and Saturn's atmosphere. From a risk perspective, two sets of orbits jumped out from the rest: the farthest four and the final five.

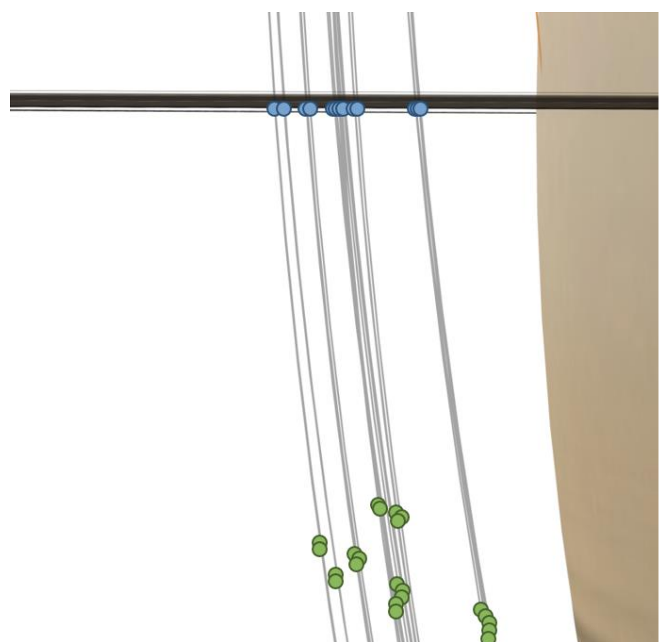

Figure 3: Orbit-normal view of the proximal corridor showing the ring-plane crossings (blue) and periapses (green).

The Farthest Four—These were the four highest orbits of the Grand Finale, which occurred during the sixth, seventh, eleventh, and twelfth proximal orbits. They appear in Figure 3 as the two gray lines farthest to the left (each line is actually two orbits, just indistinguishable at this scale). Though they do not appear to be that much higher than the next highest orbits, the ring-plane crossings of these orbits were high enough into the D ring that the dust in that region could be seen in high-phase images taken by Cassini. The other 18 orbits had ring-plane crossings below this threshold. As such, these farthest four had the highest risk of dust particle impact.

The Final Five—These were the lowest orbits in the Grand Finale by about 1000 km and are obvious in Figure 3 as the group farthest to the right. These orbits provided the best opportunity to obtain in-situ atmospheric measurements during the Grand Finale; however, they also had the greatest risk of the atmosphere overwhelming the attitude control system.

Spacecraft Protection

The Grand Finale was not the first time Cassini was to encounter dust or atmosphere. During past ring-plane crossings outside the main ring system and low altitude Titan flybys, Cassini had dealt with both dust hazards and atmospheric torques, respectively. Thus, the spacecraft had ways to mitigate the risks these environments posed and ensure its health and safety.

Dust—The spacecraft had two defenses for protecting against dust hazards: closing the main engine cover and flying High-Gain-Antenna-to-Dust-Ram (HDR). For lower risk dust hazards, the main engine cover was closed to protect the nozzles. This allowed the spacecraft to fly science-friendly attitudes while still protecting the ability to perform future main engine burns. For more moderate dust hazard risks, the spacecraft could be flown with the high gain antenna pointed in the direction of the incoming dust particles. This used the antenna as a shield to help protect the spacecraft from potentially harmful dust impacts. While this protection was more robust, it came at the cost of science. With all components of Cassini being body-fixed, pointing the antenna in the direction of dust meant that the instruments were not pointing in their desired directions. As such, HDR was implemented only when more significant threats to spacecraft health and safety were predicted.

Atmosphere—The main method for maintaining control authority in the presence of an atmosphere was achieved by switching from reaction wheels to reaction control system (RCS) thrusters. The thrusters provided about ten times the control authority of the wheels, which meant they could withstand ten times the atmospheric torque.

2. Ring Plane Crossings

The first potential hazard encountered during each proximal corridor passage was D ring dust at the ring-plane crossing. The risk to the spacecraft from this dust increased with radial distance from Saturn as that put the spacecraft farther into the D ring. Figure 4 shows the exact radial distances of all 22 ring-plane crossings of the Grand Finale (in blue). The dashed-blue line is the radius at which the D ring dust signal disappeared into the background noise of the best images Cassini had taken of that region.

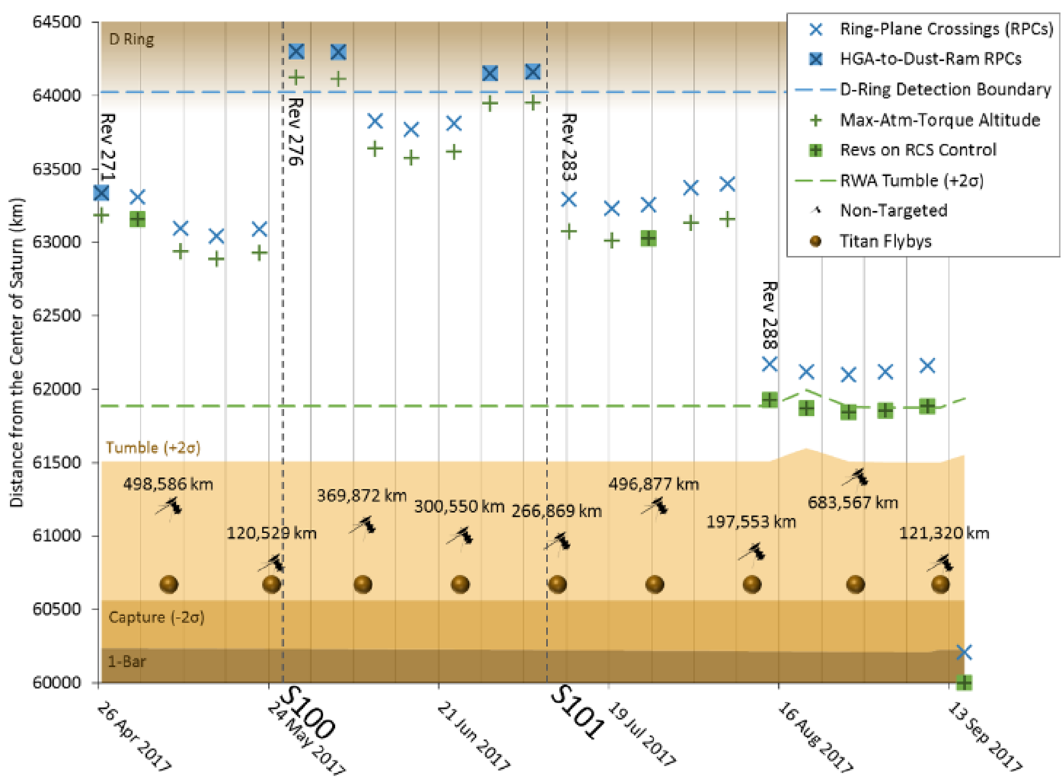

Figure 4: Radial distance of ring-plane crossings (blue) and points of maximum-atmospheric-torque (green) during the proximal orbits. The non-targeted Titan flybys causing the variations are also shown (on a separate scale).

Baseline and Contingency Plans

Given that the farthest four orbits were above the D ring detection boundary, their dust hazard risk could be directly calculated from the data. The risk was found to be of the same order of magnitude as past dust hazards that were protected with HDR [2]. As such, these four orbits were baselined with an HDR attitude. The risks to the other 17 orbits were dependent on the dust brightness trend seen above the detection threshold continuing below it. Extrapolating that trend resulted in risks that did not require HDR protection. However, given the uncertainty in the extrapolation, the project chose to fly the very first crossing with HDR and put a contingency plan in place that allowed any unprotected crossing to be commanded to an HDR attitude. Figure 4 shows the resulting baseline plan, with the first and farthest four crossings flown at HDR, while the remaining 17 were unprotected, science-prime attitudes.

As-Flown

During the first ring-plane crossing, the Radio and Plasma Wave Science instrument collected data from dust impacting the spacecraft. Analysis of that data revealed that the dust fluence was several orders of magnitude lower than predicted [4]. Thus, the contingency plan was not implemented. In fact, when the sixth and seventh crossings (the two highest) showed the same trend, the project allowed the eleventh orbit to be unprotected. This was accomplished by using the contingency plan but replacing the HDR contingency attitude with a science-friendly attitude that let the Cosmic Dust Analyzer instrument peak out from behind the antenna and sample the incoming dust particles, as shown in Figure 5.

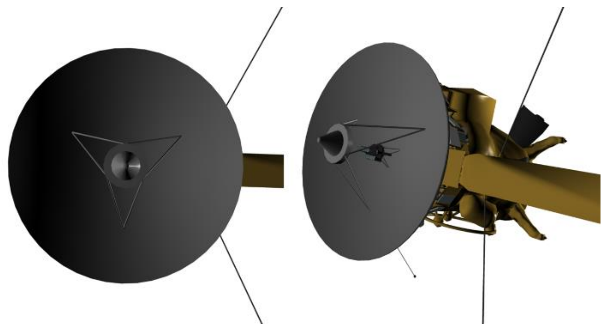

Figure 5: Cassini's eleventh crossing as viewed from the direction of the incoming dust particles. Baseline pointing on the right, as-flown on the left.

Though the dust environment was benign enough to fly a similar offset attitude for the twelfth crossing, such an attitude would have negatively impacted the science observations surrounding it. As such, that crossing was flown with the baseline HDR attitude.

3. Atmospheric Transits

About four minutes after each ring-plane crossing, Cassini would reach periapsis, bringing it to the other potential hazard in each corridor crossing, the atmosphere. Figure 4 shows the points at which the atmosphere exerts the maximum amount of torque on the spacecraft (in green), which, due to Saturn's oblateness and the orientation of the orbit, happened about a minute before periapsis proper. The dashed-green line is the radius at which the atmosphere would overwhelm the reaction wheels; thus, requiring thruster control.

Baseline and Contingency Plans

As Figure 4 shows, the only orbits that approach the wheel saturation boundary are the final five. These five orbits were flown on thruster control to ensure control authority was maintained throughout the transit. Two other orbits (the second and fifteenth) were flown on thruster control; however, this was because the science observations required the faster turning rates allowed in thruster control and not for spacecraft health and safety. A contingency plan allowed for a maneuver to be performed near the apoapsis following the first of the final five transits that would increase the subsequent periapsis radii in the event that the atmosphere proved thicker than predicted. In addition, windows for two other potential maneuvers were held after the third and fourth transits to lower the periapses of the subsequent orbits if the atmosphere was substantially thinner than predicted [5].

As-Flown

The RCS thrusters were used as atmospheric state detectors during the final five orbits, their duty-cycles being directly related to the density of the atmosphere. After the first of the final five transits, analysis of the peak duty-cycled revealed that the atmosphere was over twice as dense as predicted. While surprising, enough margin existed that the trajectory did not have to be modified by a maneuver and the remaining four transits were flown as planned. Figure 6 shows the predicted and actual duty cycles for the final five.

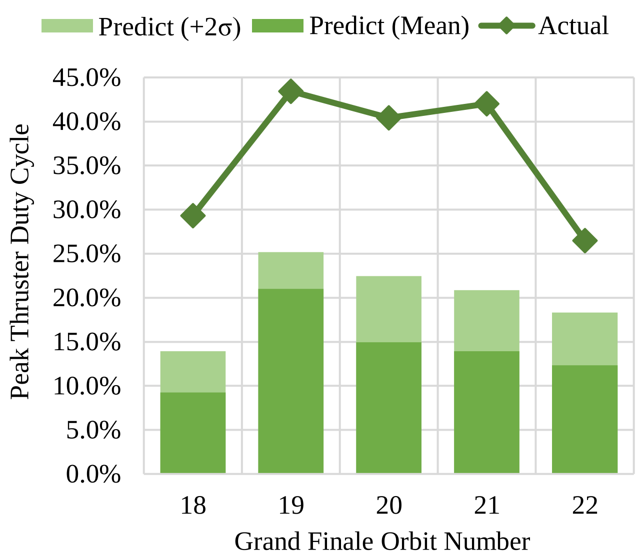

Figure 6: Predicted and actual thruster duty-cycles from the final five Grand Finale orbits.

4. END OF MISSION

The last non-targeted Titan flyby occurred just before apoapsis of the last half-orbit and set up the final plunge of the spacecraft into Saturn. The last 14.5 hours of the mission had continuous DSN coverage with the final 3.5 hours providing a near-real-time downlink. Figure 8 shows the geometry of the final orbit with the original predicted times of key events labeled.

Prior to the start of the Grand Finale, the project was predicting loss of signal to occur on September 15, 2017 at 10:45 (SCET) [6]. As the Grand Finale progressed, the navigation team updated first its Saturn gravity model and later its Saturn atmosphere model. The updates caused shifts in the predicted loss of signal time, which the mission planning team started tracking on a weekly basis. Figure 7 shows the evolution of the loss of signal predict.

The first point in Figure 7 is the reference trajectory, the trajectory used to plan the Grand Finale. The next three points show the jump that occurred with the update of the Saturn gravity model. The last five points show how the predict changed after each of the final five orbits. Table 1 shows the final loss of signal predict along with the actual times that telemetry and each of the carrier signals were lost.

The final predicted loss of signal time was less than two seconds off from the actual. The official end of mission was called at the loss of the S-band carrier, September 15, 2017 at 10:32:15.810 (SCET).

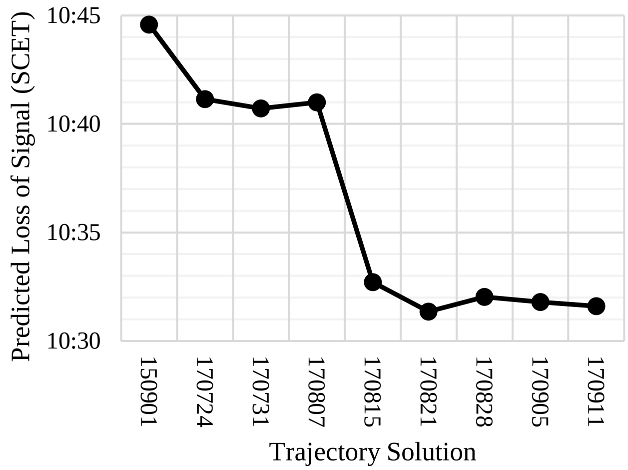

Figure 7: History of the predicted loss of signal time on September 15, 2017.

Table 1: Predicted and actual loss of signal times.

Loss Of Signal	Spacecraft Event Time
Telemetry Predict	10:31:48.700
X-band Telemetry	10:31:51.000
Ka-band Carrier	10:32:04.770
X-band Carrier	10:32:07.660
S-band Carrier	10:32:15.810

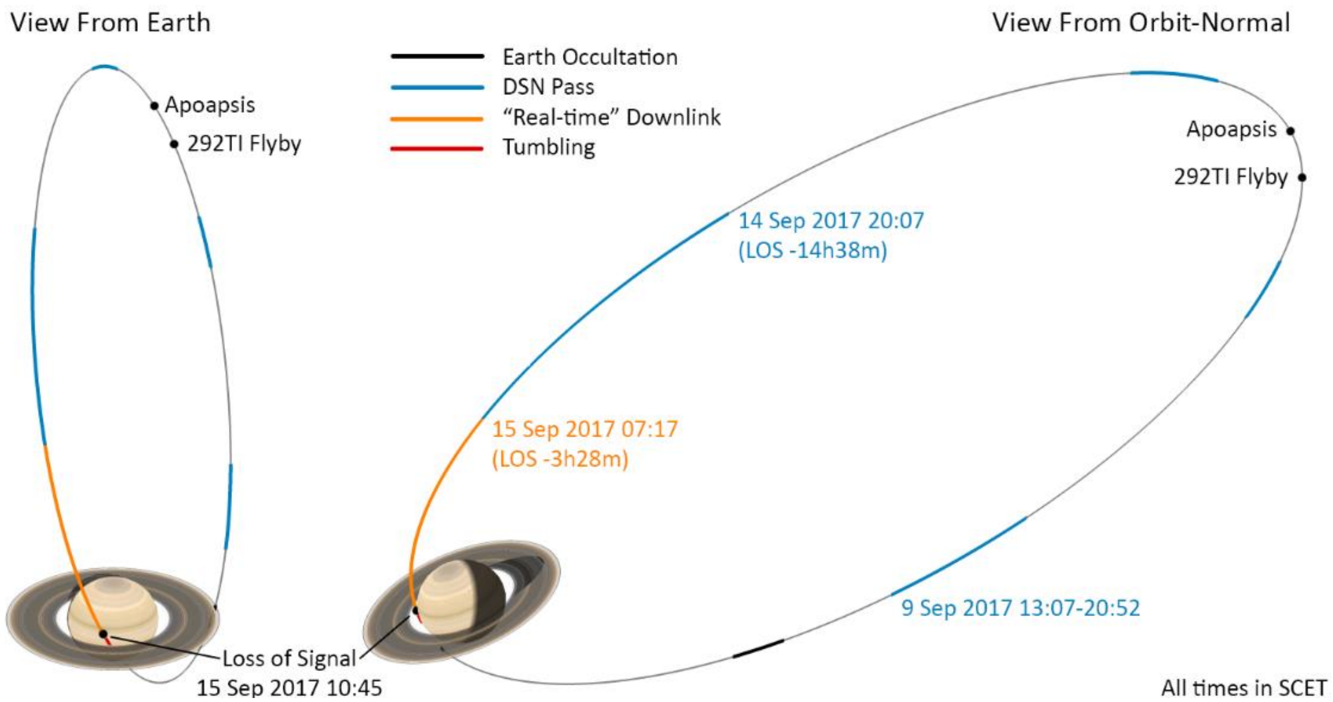

Figure 8: End-of-mission orbit geometry from Rev 292 periapsis to Saturn impact. On the left, is the view from Earth. On the right, is the view along the orbit-normal. Times shown are in spacecraft event time (SCET).

5. SUMMARY

Cassini's Grand Finale revealed that the proximal corridor was significantly different than expected. Saturn's D ring dust particle fluence was orders of magnitude lower than the images of the region suggested and its atmosphere was over twice as thick as the model derived from occultation data predicted. However, both of these surprises resulted in improved science return. The benign dust environment allowed one of the protected ring-plane crossings to assume a science-friendly attitude, while the thicker atmosphere meant the in-situ measurements taken during the final orbits were effectively sampling deeper in the atmosphere.

ACKNOWLEDGMENTS

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BIOGRAPHY

Erick Sturm *is the Mission Planning lead for the Cassini Mission. Prior to joining Cassini, he served as a mission engineer and mission architect for the Mars Advanced Formulation Office and for various planetary mission concepts. He joined JPL in 2005 fresh out of California Polytechnic State University, San Luis Obispo, where he received his B.S. in Aerospace Engineering, B.A. in Physics, and M.S. in Aerospace Engineering.*