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FLYING CASSINI THROUGH THE GRAND FINALE ORBITS: PREDICTION VS. REALITY

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After twenty years of successful mission operations and invaluable scientific discoveries, the Cassini orbiter completed its tour around the Saturnian system on the most complex gravity-assist trajectory ever flown. The end-of-mission target of September 15, 2017 was achieved by preserving propellant at the expense of minimizing maneuver cycles. A navigation a strategy that incorporated orbit trim maneuvers was developed years in advance to maintain position dispersions below 250 km (1σ) at three specific periapses. This paper reports on the actual maneuver performance and overall trajectory control to maintain the Grand Finale orbits, highlighting the differences between predicted and implemented values.

OVERVIEW

Launched on October 15, 1997 to observe Saturn and its moons, rings, and magnetosphere, the Cassini-Huygens spacecraft successfully entered Saturn orbit on July 1, 2004 and impacted the planet on September 15, 2017. The last phase of the mission, called the Grand Finale (GF), was a series of 22 highly inclined (62 degrees), short period (6.5 days), ballistic orbits each passing within a few thousand kilometers of the cloud tops of Saturn.[1] On September 15, 2017, the spacecraft dove into Saturn's atmosphere and became permanently captured. The end of mission trajectory depicted in Figure 1 was incorporated in the final phase of the Solstice Mission after multiple studies were carried out to ensure that, per Planetary Protection requirements and before the spacecraft ran out of propellant, the possibility of future impact with any of the large icy moons, such as Enceladus, was precluded.

The Cassini mission arguably represents the most complex gravity-assist trajectory ever flown,[2–4] and the last few orbits – although no moon flybys were targeted – were no less. As such, the Cassini Flight Path Control team encountered many difficulties along the way. Flying the spacecraft along such complex trajectory was a challenging task and the maneuver processes evolved and improved on a daily basis, especially during the last phase of the mission. When Cassini began its Grand Finale on April 22, 2017, navigation operations

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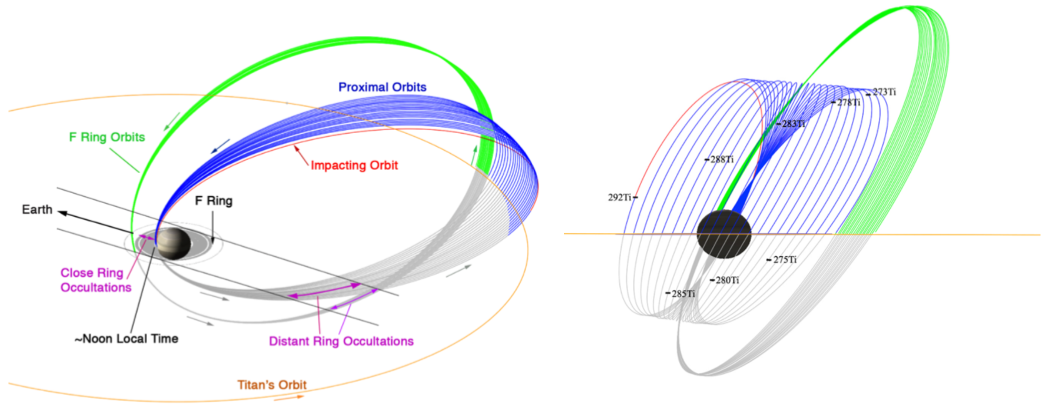


(a) (b)

Figure 1. Representation of Cassini's Grand Finale trajectory encompassing the F-ring orbits (green), the Grand Finale orbits (blue), and the final orbit (red) culminating with Saturn atmospheric entry on September 15, 2017.

underwent a paradigm shift. Unlike the primary mission, where maneuvers were designed to precisely target the desired satellite flyby conditions, the control strategy during the proximal mission was to "stay close" (within 250 km, 1σ) to the reference trajectory while minimizing the number of maneuvers and the total ΔV. To solve the problem, years before the Grand Finale began, members of the Cassini Navigation Team examined the trades and carried out analyses used to develop the maneuver strategy for controlling the trajectory during the proximal mission, focusing on two tasks: number and location of maneuvers and location of targets. Procedures were outlined and a detailed Monte Carlo analysis was conducted to strategize maneuver and target placement and to compute maneuver ΔV statistics to maintain the trajectory under such control. During the ring plane dives, Cassini got closer than ever to the planet's dense atmosphere, providing invaluable scientific data and astonishing images. However, the modeled atmospheric density turned out to be five times smaller than Saturn's actual atmospheric density, causing position deviations from the reference trajectory and an earlier loss of signal. In the next sections, we reflect on the maneuver experience during this time period, providing a thorough comparison between the planned flight path and the actual flown one.

GRAND FINALE NAVIGATION STRATEGY

The Cassini spacecraft took advantage of the substantial gravity assists provided by each Titan encounter. In fact, about 98% of the total ΔV required by the entire mission was provided by Titan alone. For reference, a Titan flyby at an altitude of 1,000 km and a $V\infty$ of 5.5 km/s supplies about 840 m/s of ΔV to Cassini, and lower-altitude flybys impart even more. The maneuvers executed by the spacecraft were minuscule in comparison. Throughout the Prime, Equinox, and Solstice phases of the tour, the nominal navigation strategy consisted of scheduling three orbit trim maneuvers between each targeted encounter, as illustrated in Figure 2 for an outbound-to-inbound leg. Note that an outbound flyby occurs after pericrone (Saturn periapsis) whereas an inbound encounter occurs before pericrone. A cleanup maneuver, about three days after an encounter, removed the orbital dispersion errors incurred by inaccuracies in the flyby conditions; a shaping maneuver, normally located near apoapsis, targeted the encounter conditions; and an approach maneuver, about three days before an encounter, refined the orbit before an encounter, if necessary. However, this navigation strategy was not applicable to the Grand Finale mission given the absence of targeted flybys.

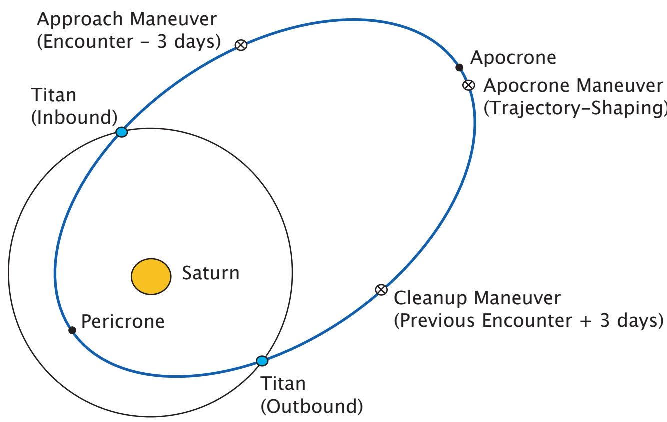
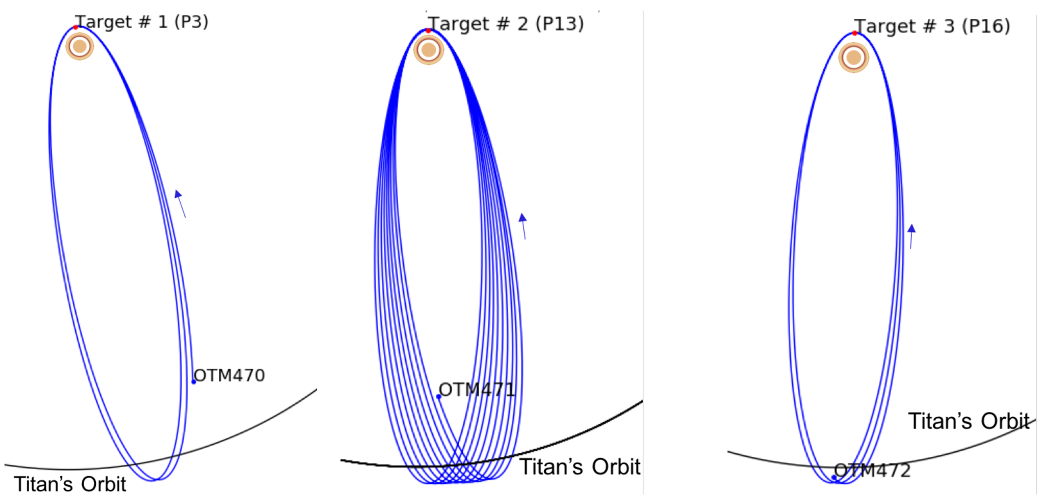


Figure 2. Schematic of the navigation strategy of three maneuvers per flyby for the Saturn tour (up to the last targeted Titan Flyby.)

The Grand Finale orbits were designed to be ballistic, i.e., no deterministic maneuvers are needed to position Cassini on its final impact trajectory. Nonetheless, the absence of targeted maneuvers throughout the final orbits causes position uncertainties to grow exponentially with time, posing a significant difficulty for the science sequence planning team, which expected to receive high volumes of unique science data from various onboard instruments. This data return is vastly improved if pointing and timing errors are reduced such that key observations can be identified and located with high precision. Thus, the flight path control strategy underwent a paradigm shift. Rather than focusing on meeting a flyby target accuracy, the goal became to incorporate a minimum amount of trajectory correction maneuvers to significantly reduce dispersions from the reference path and maintain dispersions below 250 km (1σ) for 17 out of the 22 orbits, eliminating late sequence updates and facilitating sequence planning tasks. The last five orbits did not impose a constraint on the sequence planning. An added difficulty in the design of a suitable trajectory control strategy was presented by the amount of propellant left in the tanks to maneuver the spacecraft. At the time this study took place, about 27 m/s of usable ΔV propellant was estimated to be available for maneuvers at the end of mission (at the 90th percentile), which accounts for approximately 1.1% of the mission total.

Determining the optimal number and location of the maneuvers to control the trajectory, along with the corresponding targets, was a nontrivial task. Several strategies were attempted until a feasible solution was found via two different approaches: a linear analysis to strategize maneuver and target placement[6] and a nonlinear analysis to produce final trajectory dispersions.[5] Both methods were based on orbit determination covariance sampling with Monte Carlo simulations. The linear method mapped uncertainties from a given state to a future time while the nonlinear approach was based on numerical state integration. The optimal control strategy ultimately adopted by the Cassini Project provided adequate control to most of the trajectory with only three small statistical maneuvers (predicted ΔV99 $<$ 1.5 m/s). For reasons related to science observations and sensitivities to timing errors, it was decided that there were only three periapses (periapsis-3, periapsis-14, periapsis-16) that needed to be controlled and maintained under 250 km at the 68th percentile, as opposed to attempting to maintain the first 17 orbits under this tight control. The Cassini Navigation Team then developed a three-maneuver control strategy to target periapsis-3, periapsis-13, and periapsis-16; periapsis-13 was targeted instead of periapsis-14 to lower the ΔV cost. The control points became periapsis-3 (P3) on 09-May-2017, periapsis-13 (P13) on 12-July-2017, and periapsis-16 (P16) on 01-Aug-2017. The first maneuver, Orbit Trim Maneuver # 470 (OTM470), occurred on 24-April-2017 shortly after the last targeted Titan flyby; OTM471 was implemented on 10-May-2017 and OTM472 occurred on 15-July-2017. Figure 3 illustrates all three targeting strategies carried out during the Grand Finale mission. Details about how this final targeting strategy was developed can be found in Wong et al. (2015)[5] and Vaquero et al. (2017).[6]



(a) GF Orbits 0 to 2 (b) GF Orbits 3 to 12 (c) GF Orbits 13 to 15

Figure 3. Navigation strategy for the Grand Finale mission, i.e., from post Titan-126 to Saturn impact. The blue dots represent the location of the orbit trim maneuvers implemented to control position dispersions along the trajectory, and the red dots indicate the location of the target points. Cassini's GF orbits are plotted from 24-April-2017 to 09-May-2017 in (a), from 10-May-2017 to 12-Jul-2017 in (b), and from 15-July-2017 to 01-Aug-2017 in (c). The last five revs of the Grand Finale mission were uncontrolled, and therefore, are not depicted in these graphs.

FLIGHT PATH CONTROL: PREDICTION

If left uncontrolled, that is, if no maneuvers were performed after the last approach maneuver (OTM469) before the last targeted flyby (Titan-126 on 22-Apr-2017), the overall position dispersions could grow to almost 8000 km, 1σ, as illustrated in Figure 4(a). These dispersions from the reference trajectory are a result of the Titan-126 flyby errors and spacecraft ΔV modeling errors, i.e., momentum management, Reaction Control Subsystem (RCS) thruster turns, and uncertainties in the atmospheric drag force. The goal to stay within 250 km (1σ) from the reference path at all times (if and when possible) and specifically at periapses 3, 14, and 16 is never achieved if the trajectory is left uncontrolled. The blue line represents position dispersions from the reference trajectory as a function of time; the three red circles simply highlight the controlled periapses for easier visualization. Figure 4(b) illustrates the effect of the selected control strategy: three small statistical burns allowed to maintain the position dispersions of 17 out of 22 periapses under 250 km. The first few periapses remained uncontrolled for the selected three-maneuver control strategy because controlling the first segment of the trajectory proved to require a large amount of ΔV – on the order of 25 m/s to 30 m/s – mostly due to the T126 flyby errors.[6]

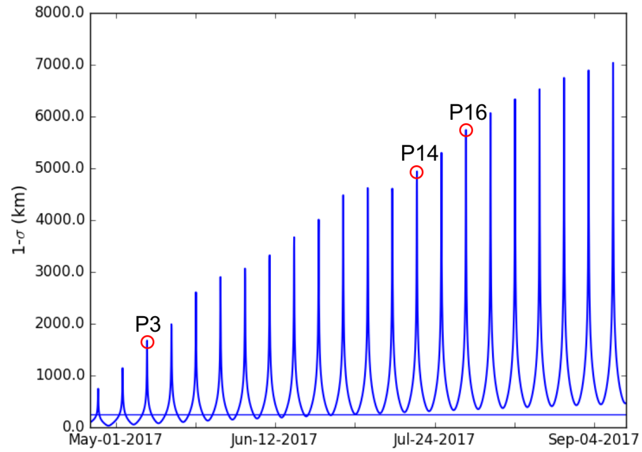
The maximum dispersions from the reference trajectory occur at periapses and are caused by along-track (timing) errors. The reference trajectory times for each of the 22 periapses during the Grand Finale are listed in Table 1 (P1 is short for Periapsis-1, which represents the first periapsis in the Grand Finale.)

Table 1. Grand Finale Periapses Times from Reference Trajectory

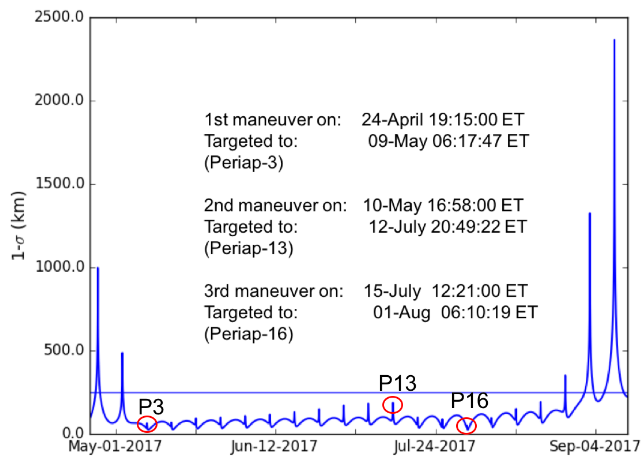
Event	Periapsis Time (ET)	Event	Periapsis Time (ET)
P1	26-Apr-2017 09:04:42.1888	P12	06-Jul-2017 09:36:42.7486
P2	02-May-2017 19:43:22.4098	P13	12-Jul-2017 20:49:22.3219
P3	09-May-2017 06:17:47.2715	P14	19-Jul-2017 07:55:57.6614
P4	15-May-2017 16:46:27.7053	P15	25-Jul-2017 19:00:31.1418
P5	22-May-2017 03:15:35.0821	P16	01-Aug-2017 06:10:19.1564
P6	28-May-2017 14:27:29.1099	P17	07-Aug-2017 17:24:20.9870
P7	04-Jun-2017 01:43:34.8965	P18	14-Aug-2017 04:24:03.3366
P8	10-Jun-2017 12:54:23.1067	P19	20-Aug-2017 15:24:35.5666
P9	16-Jun-2017 23:56:54.4513	P20	27-Aug-2017 02:21:33.5029
P10	23-Jun-2017 10:58:55.4278	P21	02-Sep-2017 13:19:00.2190
P11	29-Jun-2017 22:15:31.5965	P22	09-Sep-2017 00:19:13.3122

Contingency Pop-Up and Pop-Down Maneuvers

Three contingency maneuvers were also scheduled after OTM472 and before periapsis-19, the second of the last five periapses of the Grand Finale. Figure 5 represents the end of mission "safe" corridor; note that the last five periapses occur at a range below 62,000 km, which is the tumble boundary for the Reaction Wheel Assembly (RWA). Two contingency scenarios were considered during this last phase of the Grand Finale: 1) the atmosphere is thicker and denser than predicted, and a 'pop-up" maneuver is needed to raise periapsis and maintain the spacecraft safe from tumbling at periapsis-19 through periapsis-22; or 2)



(a) Overall uncontrolled dispersions for the 22 proximal orbits (periapsis-1 through periapsis-22) resulting from an analysis relying on linear mappings.



(b) Trajectory dispersions for the selected three-maneuver control targeting to periapsis-3, periapsis-13 and periapsis-16 based on the linear approach.

Figure 4. Trajectory dispersion results for the uncontrolled case (no maneuvers) vs. the three-maneuver control strategy case selected by the Cassini Project.[6] Peaks and troughs correspond to locations of periapsis and apoapsis, respectively, and the solid blue line at the bottom represents the 250 km control threshold.

the atmosphere is thinner and lighter than expected, and a "pop-down" maneuver is needed to lower periapsis altitude to allow better measurements of the atmosphere.

The atmosphere was assessed by Cassini mission planners at each ring plane crossing using thruster duty cycle data to determine if a "pop-up" to raise periapsis or "pop-down" to lower periapsis would be needed. Since each ring plane crossing is only 6.5 days apart and the periapsis altitude to achieve (whether higher or lower) depends on the anticipated atmosphere at each of these crossings, the targets for each contingency maneuver could not be known until just a couple of days before their executions, making the design of these

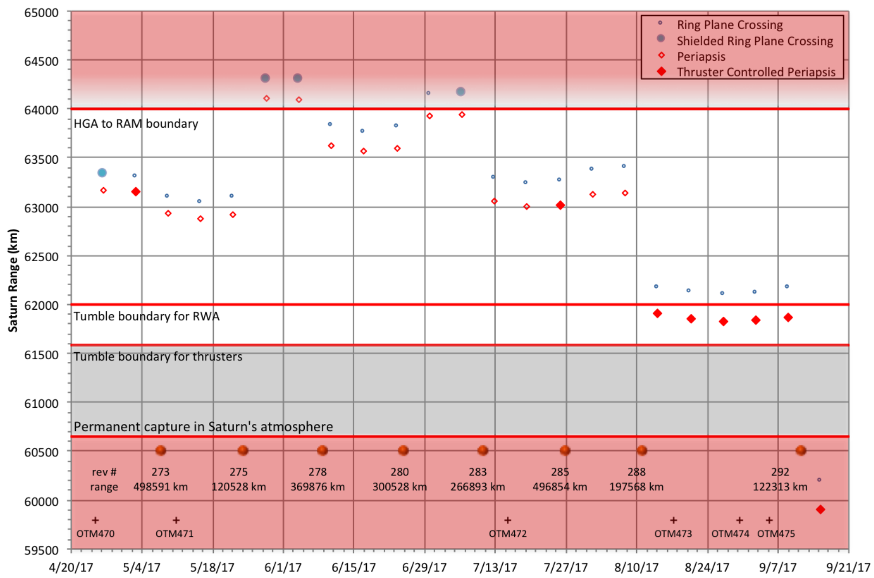


Figure 5. Schematic of Cassini's end of mission "safe" corridor: the red dots represent each of the 22 periapses locations and the solid red lines mark the three safety boundaries: High Gain Antenna (HGA) to RAM (side that points in the direction of the spacecraft's motion) to protect the instruments from any dust particles, clearance from tumbling altitude, and permanent capture into Saturn's atmosphere.

contingency burns a challenge. In the weeks prior to Cassini's plunge into Saturn, three maneuvers were designed and evaluated: OTM473, a "pop-up" maneuver (for spacecraft health and safety reasons) scheduled for August 17, 2017 and targeted to P-19; OTM474, a "pop-down" maneuver planned for August 30, 2017 and targeted to P-21, and OTM475, a "pop-down" maneuver scheduled for September 5, 2017 and targeted to P-22. As a reference, a 250 km change in periapsis altitude resulted in a maneuver magnitude of approximately 3.5 m/s. Additionally, implementing any of these three OTMs would cause significant changes from the reference trajectory.

Eventually, the atmosphere proved to be within the expected ranges and all three of these contingency maneuvers were determined to be unnecessary and were thus cancelled.

FLIGHT PATH CONTROL: REALITY

From the Titan-126 flyby to the first targeted periapsis (Periapsis-3)

The last targeted Titan flyby was a complete navigation success, with a flyby target miss of only 312 m. As such, the magnitude of the first planned Grand Finale maneuver was drastically reduced from a predicted $\Delta V99$ of 1.74 m/s to an implemented magnitude of 0.156 m/s, as listed in Table 3. The position dispersions at the targeted periapses are given in Table 4. After OTM470 was successfully implemented, the position deviation from the reference trajectory at periapsis-3 was 26 km, which is well below the predicted 1σ value of 92.6 km. It could be said that the navigation of the first three Grand Finale orbits went flawlessly.[7]

From Periapsis-3 to Periapsis-16

After periapsis-3, the Navigation Team encountered a few navigation challenges. Shortly after Cassini flew by the first targeted periapsis, the trajectory dispersions began to grow over the predicted values due to mismodeling:

- The small force predictions and c-kernels spanning the Grand Finale mission were not all available to the Orbit Determination team at start of this phase (information regarding these predictions was available only through July 8th, 2017). For reference, the small force predictions are small propulsive ΔVs, on the order of a few millimeters per second, imparted on the spacecraft from unbalanced RCS thrusting for science activities and angular momentum management of the reaction wheels. Also at this time, the RCS thruster use for momentum management and the spacecraft attitude profile were still in development. The complete set of information became available on May 16th, 2017, after the execution of both OTM470 and OTM471. Hence, all previous maneuver designs to May 16th, 2017 were based on an incomplete set of small forces.

- Unexpected drag-like forces were seen at many periapses for first half of the Grand Finale, causing the periapsis time to consistently drift earlier at each periapsis passage. This drag-like force vanished after periapsis-11 on June 29th, 2017 and the effect was reversed for later periapses, causing a systematic bias in downstream periapsis prediction times. For reference, Table 2 lists the actual periapses times along the flown trajectory.

Table 2. Grand Finale Periapses Times from Reconstructed Trajectory

Event	Periapsis Time (ET)	Event	Periapsis Time (ET)
P-1	26-Apr-2017 09:04:43.5665	P-12	06-Jul-2017 09:38:48.7385
P-2	02-May-2017 19:43:25.2340	P-13	12-Jul-2017 20:51:37.7045
P-3	09-May-2017 06:18:04.7942	P-14	19-Jul-2017 07:58:23.1454
P-4	15-May-2017 16:46:59.8881	P-15	25-Jul-2017 19:03:06.5427
P-5	22-May-2017 03:16:21.9653	P-16	01-Aug-2017 06:13:17.7851
P-6	28-May-2017 14:28:27.7823	P-17	07-Aug-2017 17:27:42.6282
P-7	04-Jun-2017 01:44:45.6042	P-18	14-Aug-2017 04:24:11.7850
P-8	10-Jun-2017 12:55:45.7060	P-19	20-Aug-2017 15:24:09.0301
P-9	16-Jun-2017 23:58:28.7697	P-20	27-Aug-2017 02:19:19.0196
P-10	23-Jun-2017 11:00:41.4025	P-21	02-Sep-2017 13:14:09.3603
P-11	29-Jun-2017 22:17:27.6147	P-22	09-Sep-2017 00:10:53.8425

- The atmospheric density estimates varied from periapsis to periapsis during the final five revs, by a factor of 2.0 to 2.6 times larger. Although this variation did not present a control issue, it made it difficult to pin down a predicted loss of signal (LoS) time, especially for media relations.

Despite the challenges encountered, especially during the last few Grand Finale orbits, the implemented navigation strategy proved to be successful and the end goal of maintaining position dispersions below 250 km at three specific periapses was met. The two primary measurements of performance were 1) predicted maneuver magnitudes vs. designed maneuver magnitudes and 2) predicted targeting accuracies vs. achieved targeting accuracies. Table 3 provides a comparison of the predicted ΔV budget vs. the actual ΔV expenditure. OTM470 was considerably smaller than anticipated thanks to the last targeted Titan flyby accuracy (sub-km miss). The effects of the mismodeling began causing larger deviations after periapsis-3 and, thus, the design and implementation of OTM471 was practically unaffected. The OTM472 magnitude ended up being higher than the predicted 1σ ΔV value, yet smaller than the predicted ΔV99 value. Overall, the total ΔV for the Grand Finale statistical maneuvers was on par with the 1σ predicted value: 0.400 m/s (predicted) vs. 0.321 m/s (designed).

Table 3. Grand Finale Maneuver Statistics

Maneuver	ΔV	Predicted Magnitude	Design Magnitude
	mean	0.59	
OTM470	1σ	0.38	0.156
	99%	1.74	
	mean	0.14	
OTM471	1σ	0.10	0.020
	99%	0.44	
	mean	0.06	
OTM472	1σ	0.04	0.145
	99%	0.19	
	mean	0.78	
Total	1σ	0.40	0.321
	99%	1.94	

More relevant to the sequence planning and science teams were the position dispersions from the reference trajectory at periapsis-3, periapsis-14, and periapsis-16. Table 4 lists a comparison between the predicted position error before the Grand Finale mission started and the actual position dispersions. The predicted position dispersion values at P3, P14, and P16 were derived from earlier analyses detailed in Wong et al. (2015)[5] and Vaquero et al. (2017).[6] Additionally, Figure 6 shows the final position dispersions from the reference trajectory as a function of time. For reference, the location of each control maneuver is represented by a red line and the solid green line indicates the 250 km (1σ) requirement. Although the predicted dispersion value for P14 was lower than the achieved value, the actual position errors at P3, P14, P16 were below the threshold control value of 250 km, especially at the last targeted periapsis, were the dispersion from the reference trajectory was only 7 km.

Table 4. Grand Finale Position Dispersion Statistics

Periapsis No.	Predicted Position Error	Actual Position Error
Periapsis-3	92.6 km	26 km
Periapsis-14	118.8 km	198 km
Periapsis-16	91.2 km	7 km

Despite the tight trajectory control, a large number of science observation updates were required throughout the Grand Finale mission. Fifteen ephemeris deliveries were made to

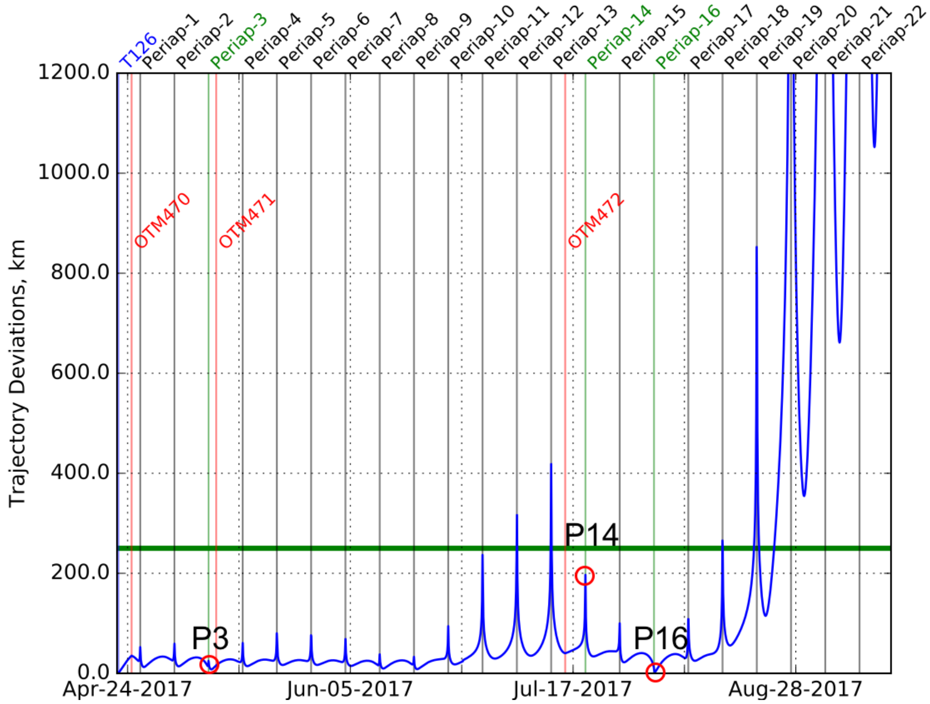


Figure 6. Actual position dispersions from the reference trajectory throughout the Grand Finale Mission.

support 16 science observation updates; of these 16 update opportunities, only 11 were implemented. Five were canceled because changes from previous ephemerides were small enough and deemed negligible. The loss of signal time was not controlled. Up to the last update, studies indicated that the LoS time could vary buy up to 88 seconds (1σ). However, the LoS radius was achieved 729.4 seconds earlier than the reference trajectory. Later analysis showed that the atmospheric density modeled for the reference trajectory was approximately 5 times smaller than Saturn's actual atmospheric density.

CONCLUSION

The plan for Cassini to plunge into the atmosphere of Saturn was carefully crafted and flawlessly executed, both from a science and engineering perspective. Cassini transmitted data to Earth to the very end, providing the first ever direct measurements of the composition of ring particles and the highest resolution yet of main ring observations. From a navigation perspective, the designed control strategy was successfully implemented and the total ΔV was well within the budgeted amount (below the 1σ value of 0.40 m/s.) Similarly, the goal of maintaining the position dispersions below 250 km (1σ) at three key periapses was fully met, especially at the last targeted periapsis, were Cassini ended up being only 7 km off its reference path. Undoubtedly, this enormous success is a direct result of years of in-flight operations experience, including the design of over 500 maneuvers and the implementation of exactly 360 maneuvers to accurately target a total of 160 flybys of Titan, Enceladus, and several of the icy moons.

ACKNOWLEDGMENT

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