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CASSINI MANEUVER EXPERIENCE THROUGH THE LAST ICY SATELLITE TARGETED FLYBYS OF THE MISSION

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The Cassini spacecraft will reach its spectacular end-of-mission in September 2017, after having spent a successful twenty years in space gathering invaluable scientific data about Saturn, its rings, and moons. Cassini has flown the most complex gravity-assist trajectory ever designed, which requires frequent maneuvering to achieve the desired targets. After so many years in operation the propellant is starting to dwindle, making it of paramount importance that the maneuvers be designed to prioritize preserving propellant. This paper highlights the strategies for 50 planned maneuvers during twelve Titan flybys and the last Dione and Enceladus flybys of the mission.

MISSION OVERVIEW

The Cassini spacecraft was launched in October 1997 and began the journey toward one of the most complex gravity-assist trajectories ever flown. It entered orbit around Saturn in July 2004 for a nominal four-year *Prime Mission* to study the Saturnian system.[1] Two extended missions followed the Prime Mission: the two year *Equinox Mission*, starting in September 2008,[2] and the seven year *Solstice Mission*, starting in September 2010.[3] The Solstice Mission spans two Saturnian seasons, increasing the mission lifetime past Saturn's northern summer solstice in May 2017 (see Figure 1). Towards the end of its mission, Cassini will pass 22 times within a few thousand kilometers of the cloud tops of Saturn, ultimately impacting Saturn in September 2017.[3,4]

The Cassini Maneuver Team (a part of the Cassini Navigation Team) designs the necessary maneuvers to maintain the prescribed reference trajectory. Previous papers have reported on the maneuver experience during Cassini's first four years of the Solstice Mission.[5,6,7,8] The goal for the navigation team is to design the maneuvers to stay as close as possible to the reference trajectory. In addition, to accommodate the end-of-mission, the maneuver decision process was refined at the beginning of the Solstice Mission to prioritize preserving propellant over minimizing maneuver cycles. The maneuvers are generally targeted to three B-plane flyby conditions of the upcoming encounter: time-of-flight and the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$.[9] This paper focuses on the maneuvers designed past the fifth year, from June 2014 to December 2015, spanning 50 planned Orbit Trim Maneuvers (OTM) to target seventeen satellite encounters: twelve with Titan (T102–T114), three with Enceladus (E20–E22), and two with Dione (D4–D5). The flybys to encounter Dione and Enceladus were the last targeted icy satellite flybys of the mission.

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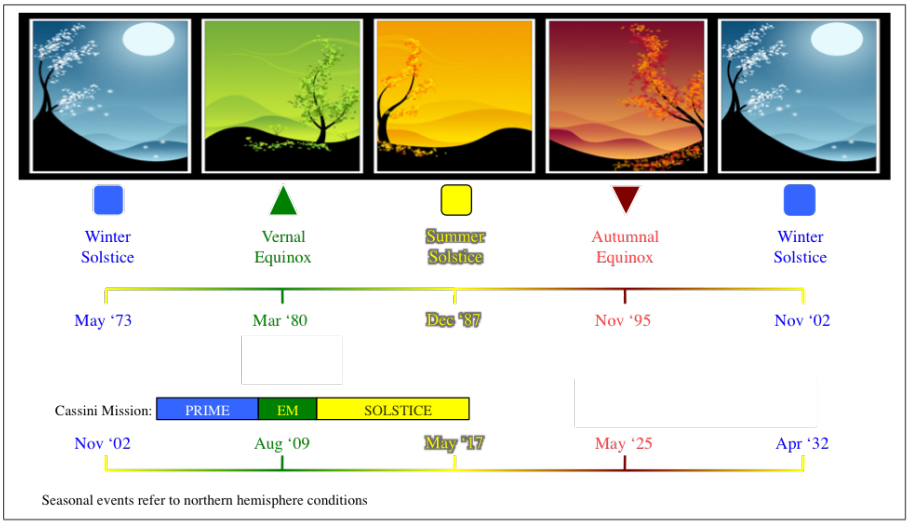
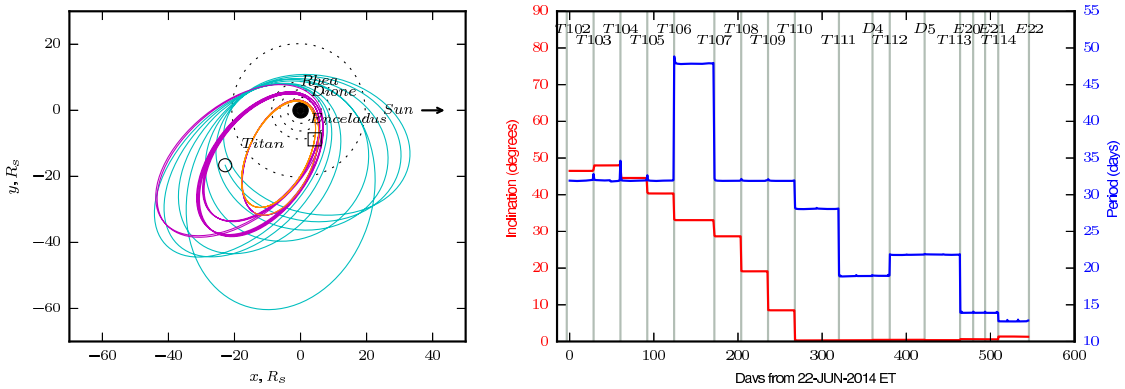


Figure 1: Saturn Seasons in the Northern Hemisphere

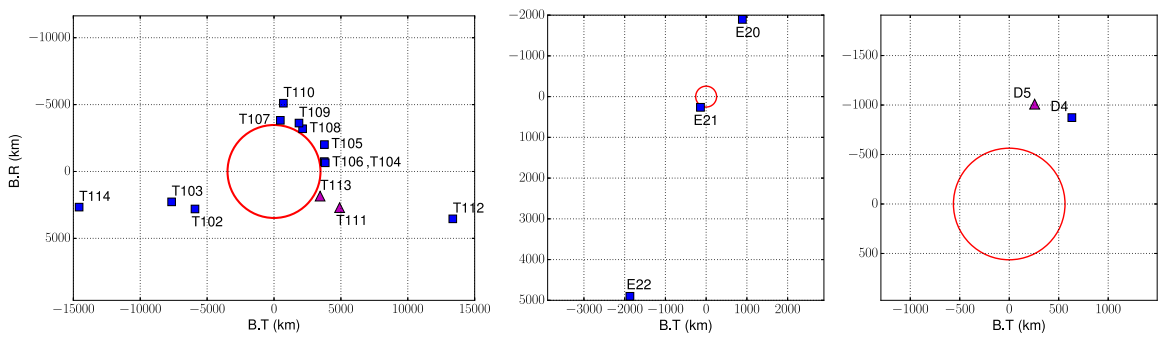


(a) (b)

Figure 2: (a) Cassini's trajectory from 18-Jun-2014 (circle) to 19-Dec-2015 (square) as viewed from Saturn's north pole. The **In-2C** phase is shown from 18-Jun-2014 to 12-Feb-2015 in cyan. After In-2C, the **Eq-2** is shown in magenta, ending on 28-Oct-2015. The beginning of **In-3** phase is shown in orange until 19-Dec-2015 at the E22 flyby. (b) Cassini's osculating inclination with respect to Saturn's true equator (red, left axis) and orbital period (blue, right axis). Encounters are labeled to highlight the effect of each flyby on the orbital parameters.

The petal plot presented in Figure 2(a) depicts the spacecraft trajectory from June 2014 to December 2015 as viewed from Saturn's north pole, with the Sun direction along the horizontal axis. The time profile of orbital inclination and orbital period, from which it is possible to determine the orbital effect of each flyby, is shown in Figure 2(b). The location of each targeted flyby discussed in this paper is plotted in the B-plane in Figure 3. Generally, the geometry of each targeted flyby is driven by a particular science objective. The planned maneuvers between T102 and T109 were

OTM-383 through OTM-403, which encompass the end of the Second Inclined Phase (**In-2**) of the Solstice Mission (cyan trajectory in Figure 2(a)). T102 and T103 increase inclination to achieve two Titan occultations for atmospheric studies of Titan's southern polar regions. These are high altitude flybys, which were beneficial since the duration of the occultations was increased, enhancing the signal measurement. T104 to T109 were low altitude flybys, and the groundtracks were all at high northern latitudes around the lakes region. The Second Equatorial Phase (**Eq-2**) encompassed OTM-404 through OTM-427, which included two close flybys of both Enceladus and Dione. This part of the mission is plotted in magenta in Figure 2(a) and can easily be spotted in Figure 2(b) because of its near zero inclination. Orbit apoapsis was rotated to precisely setup the node for the inclined proximal orbits at the end of the Solstice Mission and to enable a low ΔV cost to target E21's plume passage near the end of this equatorial phase–the last and closest plume passage of the Cassini mission. Gravity measurements were taken during the D5 flyby to help determine if Dione is geologically active. The T110 Titan groundtrack was designed for observations of the northern lakes region. The remaining T111 to T113 groundtracks were near Titan's equatorial plane. OTM-428 through OTM-433 occurred during the Third Inclination Phase (**In-3**) (orange trajectory in Figure 2(a)). Here, the T114 transfer increased inclination to 1.3° to setup the E22 distant (5000 km) south polar flyby providing ideal observational geometry for thermal and multispectral imaging of the "tiger stripe" region, similar to E11. E22 was the last targeted Enceladus flyby of the Cassini mission. About five hours prior to E22, the spacecraft passed within 2600 km of a tiny (∼0.5 km) moonlet near the center of the G ring believed to be the source of the G ring.



(a) Titan Encounters (b) Enceladus Encounters (c) Dione Encounters

Figure 3: Targeted encounter locations with Titan, Enceladus, and Dione in the B-Plane. Note, axis are scaled differently for (a), (b), and (c).

A diagram with specific orbital events is in Figure 4 to provide the context of how each maneuver relates to each targeted encounter (red). In general, there are three planned maneuvers between encounters. Each row corresponds to one revolution around Saturn; each revolution is numbered, and the period between two consecutive passes through apoapsis is listed in days. One revolution spans 360 degrees of true anomaly (the horizontal axis), negative from apoapsis (180 deg) to periapsis (0 deg), and positive from periapsis to apoapsis. Maneuvers are color-coded as either executed (blue) or cancelled (green). Out of the 50 planned OTMs encompassed from T102 to E22, 30% of them were cancelled, due in part to the ballistic nature of this portion of the mission and in part to the successful navigation strategy.

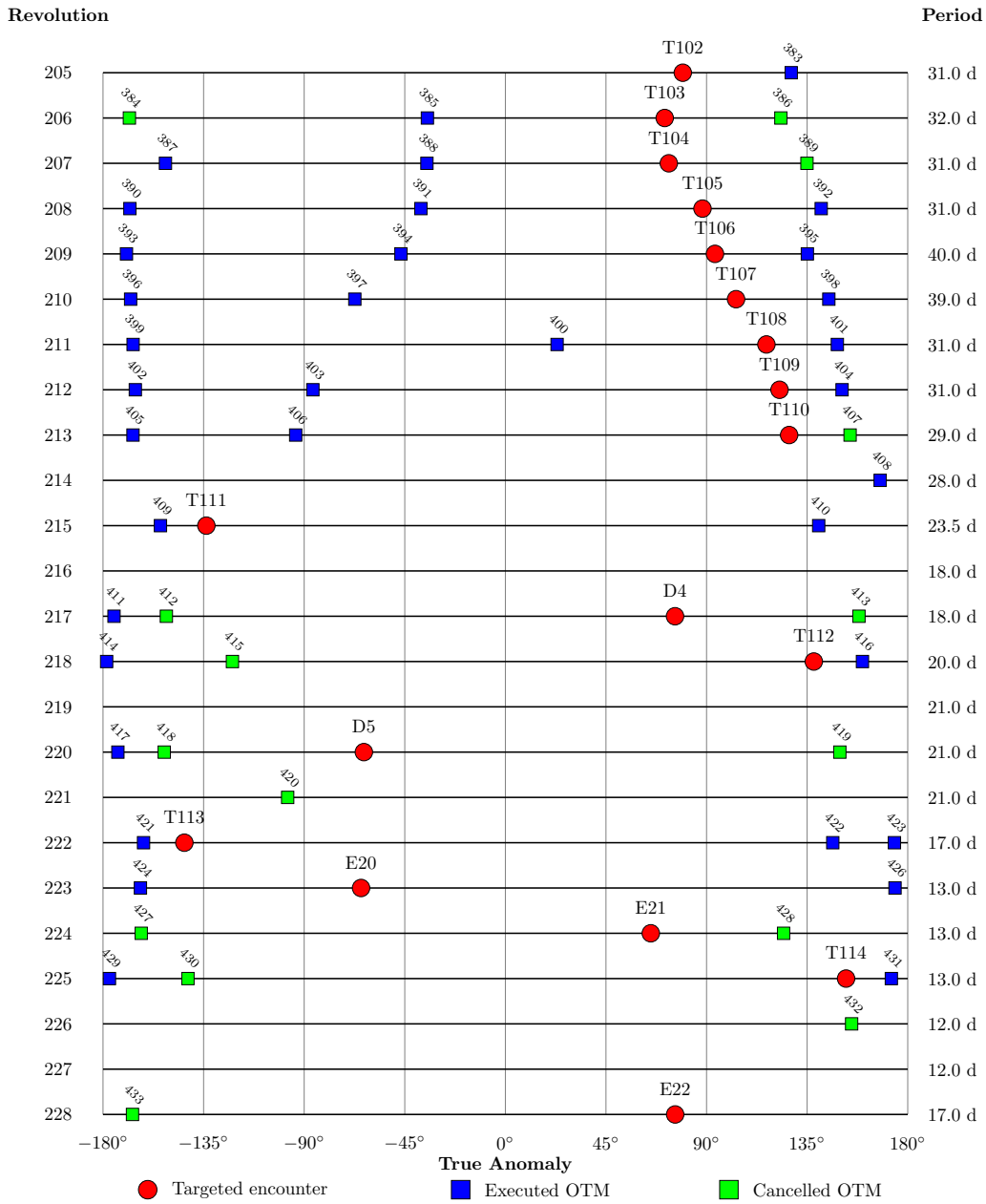


Figure 4: Titan-102−Enceladus-22 Orbital Events.

NAVIGATION STRATEGY

The Cassini spacecraft takes advantage of the large gravity assists provided by each close encounter with Titan. For example, a Titan flyby at an altitude of 1,000 km and a V_∞ of 5.5 km/s supplies about 840 m/s of ΔV to Cassini; lower-altitude flybys impart even more. The maneuvers executed by Cassini are small in comparison: about 98% of the total ΔV required by the entire mission is provided by Titan alone. The main goal of the navigation team is to design the maneuvers to stay as close as possible to the reference trajectory. However, to accommodate the end-of-mission,

the maneuver decision process was refined at the beginning of the Solstice Mission to prioritize preserving propellant over minimizing maneuver cycles.[5] This maneuver approach yields a propellant savings by minimizing the ΔV cost across several downstream maneuvers, as opposed to canceling a maneuver (which, in contrast, could add ΔV to future maneuvers).

The nominal navigation strategy is to employ three propulsive maneuvers between each encounter (see Figure 5). The maneuvers are generally targeted to three B-plane flyby conditions of the upcoming encounter: time-of-flight and the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$. These targets were determined during the mission design phase, and are collectively known as the reference trajectory. A cleanup maneuver, approximately three days after an encounter, removes the dispersion errors caused by inaccuracies in the flyby; a trajectory-shaping maneuver, normally located near apocrone (Saturn apoapsis), targets the encounter conditions; and, if necessary, an approach maneuver refines the trajectory three days before the encounter. Typically, the cleanup and apoapsis maneuvers are deterministic: their executions are usually required, and they are normally optimized together in a chained two-impulse optimization strategy, which minimizes total deterministic ΔV across several encounters, while controlling asymptote errors without altering downstream flyby aimpoints after each encounter.[10] On the other hand, the approach maneuver is typically statistical: its execution depends on the accumulation of random error.

Maneuvers are performed by using Cassini's Main Engine Assembly (MEA) for larger maneuvers or Reaction Control Subsystem (RCS) for smaller maneuvers (see Figure 6). RCS consists of four hydrazine thruster clusters grouped into two sets: the first set is along $\pm\mathbf{Y_{S/C}}$, and is used to make balanced roll turns about the $\mathbf{Z_{S/C}}$ axis; the second set faces the $-\mathbf{Z_{S/C}}$ axis and is used to make unbalanced yaw turns about the $\mathbf{Y_{S/C}}$ axis. RCS is used for attitude control, reaction wheel momentum dumps, and small maneuvers (ΔV $<$ 0.25 m/s). MEA is utilized for larger burns if the predicted burn time is at least 1.5 sec. This burn duration minimum was set to avoid a software limitation of 1 sec for burn times,[6] which translates to MEA burns that are at least 0.25 m/s. Besides concentrating on saving propellant by minimizing ΔV cost, the maneuver approach also involves avoiding unnecessary MEA burns, due to the dwindling of bi-propellant on Cassini.

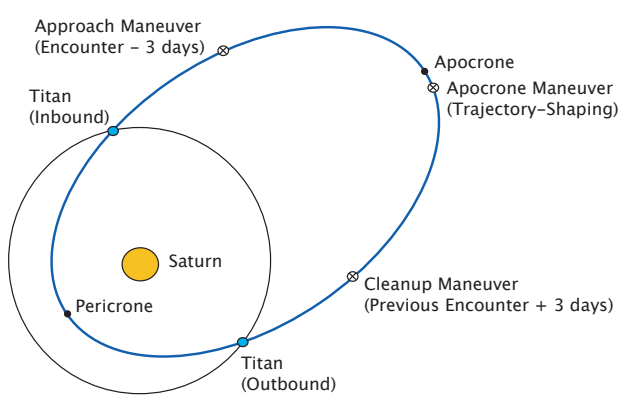


Figure 5: Navigation Strategy for Saturn Tour Mission

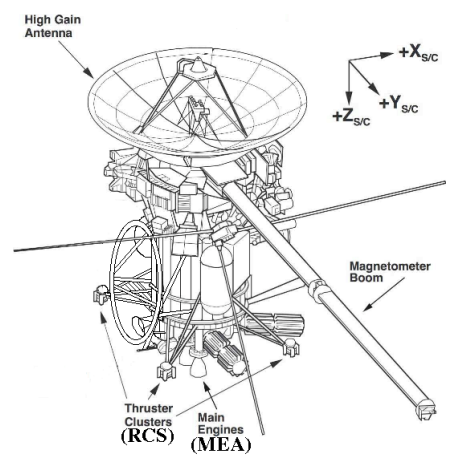


Figure 6: Cassini Orbiter

Each maneuver is executed in a turn-and-burn manner: the required burn attitude is achieved by performing a roll turn followed by a yaw turn (wind turns), the burn is then executed and, after completion, the turns are reversed to return to the original attitude (unwind turns). Turns performed

with the Reaction Wheel Assembly (RWA) and roll turns performed by RCS do not impart ΔV to the spacecraft. Moreover, yaw turns executed by RCS do contribute ΔV because these thrusters are unbalanced about the $\mathbf{Y_{S/C}}$ axis. All roll turns and the yaw turn for RCS maneuvers are typically executed by the RWA. However, the yaw turn for MEA maneuvers is usually performed by RCS thrusters. For this reason, the computation of MEA maneuvers needs to account for the ΔV imparted by the turns.

A planned maneuver can be cancelled if it is determined that its execution will not improve encounter conditions, yield downstream ΔV savings, or if a subsequent maneuver can attain the encounter conditions at a lower ΔV cost. For example, an approach maneuver might be cancelled if it is preceded by an accurate shaping maneuver. The decision to cancel such maneuver is usually subject to science requirements, as well as the decision to slightly modify targeting parameters. Such modification can be necessary either (a) when a maneuver is smaller than the smallest implementable maneuver (approximately 10 mm/s) (in this case, it is possible to modify the encounter time by a few tenths-of-a-second and artificially increase the maneuver magnitude) or (b) when changing the target spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ can yield downstream ΔV savings*.

RECONSTRUCTION OF MANEUVERS AND TARGETED FLYBYS

The maneuver design and reconstruction history from June 18, 2014 through December 19, 2015, covering OTMs 383–433, is presented in Table 1. The table lists the maneuver epoch, true anomaly, central angle, design and reconstructed ΔVs (magnitude, right ascension, and declination), and engine type (main engine or RCS). The reported true anomaly corresponds to the instantaneous Saturn-centered orbit at burn time. The central angle is defined by the three-dimensional angle between the position vectors at the burn time and encounter (counting multiple revolutions). Maneuvers are grouped by the corresponding targeted encounters; the shaded rows contain the encounter name, time of closest approach, flyby altitude, flyby ΔV imparted to spacecraft, and the days to the next encounter.

The ΔV characteristics of each maneuver covered in the scope of this paper are listed in Table 2, including the maneuver location (true anomaly and central angle), the ΔV magnitude, the roll and yaw turn angles for burn orientation, and the burn durations. Each maneuver has both prime and backup designs. Backup maneuver windows are scheduled approximately 24 hours after the prime maneuver windows. Data from executed maneuvers are shaded in blue, and data from main engine maneuver designs are indicated in bold. Out of 50 planned maneuvers (OTMs 383–433), 14 maneuvers were canceled. Out of the 36 performed maneuvers, only 8 were performed with MEA.

The targeted encounter conditions and the reconstructed flyby differences for each of the 18 flybys from T102 to E22 are provided in Table 3. Changes in the B-Plane target position (T105 and T114) or in the encounter time (T107, T110, T111) are highlighted in this table, as well as in Table 1. For reference, the total number of intentionally altered flybys up to date in the Solstice Mission is 19, as compared to the Prime and Equinox Missions total of 6.

SPACECRAFT OPERATIONS

The planned maneuvers between Titan-102 (18-June-2014) and Enceladus-22 (10-Dec-2015) encompass three different phases of Cassini's Solstice Mission: The end of **In-2C** encompasses Titan-102 through Titan-109, **Eq-2** encompasses Titan-109 through Titan-113, including two close flybys

*About 1 gram of hydrazine per mm/s is saved for RCS-sized maneuvers

Table 1: Maneuver History (OTMs 383–433)

Maneuver	Orbit Location	Maneuver Time (UTC SCET)	True Anomaly (deg)	Central Angle (deg)	Total Design $\Delta\mathbf{V}^*$ Mag. (m/s)	RA (deg)	Dec. (deg)	Total Reconstructed $\Delta\mathbf{V}^*$ Mag. (m/s)	RA (deg)	Dec. (deg)	Burn Type
Titan-102 (T102): 18-Jun-2014 13:29:32 ET, Altitude= 3659 km, Flyby ΔV= 511.6 m/s, 31.9 days to T103											
OTM-383	T102+4d	22-Jun-2014 04:59	127.88	309.72	0.046	257.13	8.84	0.045	256.94	8.92	RCS
OTM-384	∼apo	05-Jul-2014 03:58	−168.19	245.84	...	...	...	*CANCELLED*	...	...	
OTM-385	T103−3d	17-Jul-2014 09:40	−34.88	112.62	0.032	91.32	−38.16	0.032	91.48	−38.24	RCS
Titan-103 (T103): 20-Jul-2014 10:42:05 ET, Altitude= 5103 km, Flyby ΔV= 419.2 m/s, 31.9 days to T104											
OTM-386	T103+4d	24-Jul-2014 02:40	123.24	306.71	...	...	...	*CANCELLED*	...	...	
OTM-387	∼apo	09-Aug-2014 08:08	−151.68	221.73	12.460	277.60	30.58	12.466	277.65	30.67	MEA
OTM-388	T104−3d	18-Aug-2014 07:37	−35.10	104.86	0.032	172.00	7.48	0.032	172.02	7.31	RCS
Titan-104 (T104): 21-Aug-2014 08:10:16 ET, Altitude= 964 km, Flyby ΔV= 866.1 m/s, 31.9 days to T105											
OTM-389	T104+4d	25-Aug-2014 07:06	134.92	310.65	...	...	...	*CANCELLED*	...	...	
OTM-390	∼apo	07-Sep-2014 06:19	−167.95	253.56	1.266	257.69	12.62	1.262	257.69	12.75	MEA
OTM-391†	T105−3d	19-Sep-2014 05:33	−37.80	123.44	0.084	257.97	42.31	0.086	257.39	42.36	RCS
Titan-105 (T105): 22-Sep-2014 05:24:26 ET, Altitude= 1400 km, Flyby ΔV= 777.5 m/s, 31.9 days to T106, $\Delta(\mathbf{B}\cdot\mathbf{R}, \mathbf{B}\cdot\mathbf{T}) = (-1.0, +1.0)$ km											
OTM-392	T105+4d	26-Sep-2014 05:02	141.29	315.98	0.066	322.56	27.96	0.067	322.17	28.15	RCS
OTM-393	∼apo	09-Oct-2014 04:16	−169.51	266.82	1.065	71.17	5.25	1.061	71.11	5.20	MEA
OTM-394	T106−3d	21-Oct-2014 03:30	−46.70	144.03	0.036	52.70	−48.85	0.036	52.36	−49.12	RCS
Titan-106 (T106): 24-Oct-2014 02:41:37 ET, Altitude= 1013 km, Flyby ΔV= 854.5 m/s, 47.8 days to T107											
OTM-395	T106+4d	27-Oct-2014 20:44	135.09	320.33	0.062	288.05	48.44	0.063	287.54	48.44	RCS
OTM-396	∼apo	22-Nov-2014 01:44	−167.65	263.10	0.198	112.05	−7.40	0.196	112.26	−7.85	RCS
OTM-397†	T107−3d	07-Dec-2014 18:30	−67.33	162.81	0.037	305.11	−47.57	0.037	305.08	−47.39	RCS
Titan-107 (T107): 10-Dec-2014 22:27:42 ET, Altitude= 980 km, Flyby ΔV= 864.0 m/s, 31.9 days to T108, $\Delta TF = +0.4$ sec											
OTM-398	T107+3d	14-Dec-2014 00:15	144.70	329.29	0.161	237.86	60.12	0.161	237.27	59.82	RCS
OTM-399	∼apo	29-Dec-2014 23:31	−166.54	280.58	0.968	78.87	27.15	0.965	78.89	27.04	MEA
OTM-400	T108−3d	08-Jan-2015 22:47	−72.18	186.18	...	...	...	*CANCELLED*	...	...	
OTM-400 BU	T108−2d	09-Jan-2015 22:47	23.14	90.83	0.056	99.39	−51.07	0.056	99.31	−51.57	RCS
Titan-108 (T108): 11-Jan-2015 19:49:42 ET, Altitude= 970 km, Flyby ΔV= 865.3 m/s, 31.9 days to T109											
OTM-401	T108+3d	14-Jan-2015 22:32	148.51	331.96	0.229	238.38	27.92	0.229	238.19	27.56	RCS
OTM-402	∼apo	31-Jan-2015 21:34	−165.55	286.08	1.268	84.12	47.53	1.273	84.12	47.34	MEA
OTM-403	T109−3d	09-Feb-2015 21:06	−86.11	206.59	0.029	245.27	−23.58	0.030	245.14	−23.39	RCS
Titan-109 (T109): 12-Feb-2015 17:09:11 ET, Altitude= 1200 km, Flyby ΔV= 816.5 m/s, 31.9 days to T110											
OTM-404	T109+3d	15-Feb-2015 20:36	150.63	333.52	0.497	251.42	6.57	0.495	251.21	6.86	MEA
OTM-405	∼apo	04-Mar-2015 19:39	−166.58	290.77	0.100	331.07	6.97	0.100	330.76	7.06	RCS
OTM-406†	T110−3d	13-Mar-2015 19:10	−93.80	217.94	0.023	193.76	−21.25	0.022	194.12	−21.46	RCS
Titan-110 (T110): 16-Mar-2015 14:30:55 ET, Altitude= 2275 km, Flyby ΔV= 647.1 m/s, 52.3 days to T111, $\Delta TF = -0.7$ sec											
OTM-407	T110+3d	19-Mar-2015 18:41	154.21	438.91	...	...	...	*CANCELLED*	...	...	
OTM-408	∼apo	20-Apr-2015 16:29	167.67	65.43	0.047	195.37	−1.63	0.046	195.48	−1.84	RCS
OTM-409†	T111−3d	04-May-2015 15:30	−154.30	27.43	0.018	164.85	0.58	0.019	164.74	0.55	RCS
Titan-111 (T111): 07-May-2015 22:51:30 ET, Altitude= 2721 km, Flyby ΔV= 594.9 m/s, 39.9 days to D4, $\Delta TF = -0.7$ sec											
OTM-410	T111+4d	11-May-2015 15:00	140.16	656.09	0.061	70.01	−1.95	0.061	69.90	−2.22	RCS
OTM-411	∼apo	08-Jun-2015 13:00	−175.08	251.19	0.060	165.60	−8.99	0.060	165.85	−9.11	RCS
OTM-412	D4−3d	13-Jun-2015 12:45	−151.66	227.76	...	...	...	*CANCELLED*	...	...	
Dione-4 (D4): 16-Jun-2015 20:12:59 ET, Altitude= 517 km, Flyby ΔV= 18.5 m/s, 20.5 days to T112											
OTM-413	D4+4d	20-Jun-2015 12:14	158.18	342.08	...	...	...	*CANCELLED*	...	...	
OTM-414	∼apo	26-Jun-2015 11:44	−178.38	318.67	0.070	184.45	1.84	0.071	184.59	1.54	RCS
OTM-415	T112−3d	04-Jul-2015 11:13	−122.11	262.39	...	...	...	*CANCELLED*	...	...	
Titan-112 (T112): 07-Jul-2015 08:10:58 ET, Altitude= 10953 km, Flyby ΔV= 237.3 m/s, 41.4 days to D5											
OTM-416	T112+3d	10-Jul-2015 10:58	159.74	497.05	0.096	34.65	−5.09	0.096	34.22	−5.03	RCS
OTM-417	∼apo	09-Aug-2015 08:54	−173.35	110.04	0.018	143.44	−5.41	0.018	143.71	−5.59	RCS
OTM-418	D5−3d	14-Aug-2015 08:23	−152.61	89.32	...	...	...	*CANCELLED*	...	...	
Dione-5 (D5): 17-Aug-2015 18:34:33 ET, Altitude= 479 km, Flyby ΔV= 21.8 m/s, 42.1 days to T113											
OTM-419	D5+4d	21-Aug-2015 08:07	149.62	436.12	0.058	54.06	−2.77	0.057	53.79	−2.91	RCS
OTM-420	∼peri	08-Sep-2015 06:50	−97.38	323.15	...	...	...	*CANCELLED*	...	...	
OTM-421	T113−4d	25-Sep-2015 05:48	−161.87	27.51	0.022	123.70	−7.43	0.022	123.90	−7.58	RCS
Titan-113 (T113): 28-Sep-2015 21:38:20 ET, Altitude= 1036 km, Flyby ΔV= 849.0 m/s, 15.5 days to E20											
OTM-422	T113+3d	02-Oct-2015 05:17	146.47	148.98	0.252	247.12	−18.14	0.246	246.77	−17.59	MEA
OTM-423	∼apo	06-Oct-2015 05:02	174.06	121.39	2.626	219.59	−79.49	2.623	220.24	−79.58	MEA
OTM-424	E20−3d	11-Oct-2015 04:46	−163.26	98.71	0.034	158.22	−7.71	0.034	158.36	−7.84	RCS
Enceladus-20 (E20): 14-Oct-2015 10:42:37 ET, Altitude= 1846 km, Flyby ΔV= 0.8 m/s, 14.2 days to E21											
OTM-426	∼apo	20-Oct-2015 04:15	174.31	251.04	0.070	105.18	−0.56	0.071	105.22	−0.89	RCS
OTM-427	E21−3d	25-Oct-2015 04:00	−162.90	228.25	...	...	...	*CANCELLED*	...	...	
Enceladus-21 (E21): 28-Oct-2015 15:23:49 ET, Altitude= 50 km, Flyby ΔV= 5.7 m/s, 15.6 days to T114											
OTM-428	E21+1d	29-Oct-2015 03:45	124.45	386.29	...	...	...	*CANCELLED*	...	...	
OTM-429†	∼apo	05-Nov-2015 03:29	−177.12	327.87	0.111	319.54	−4.71	**TBD**	**TBD**	**TBD**	RCS
OTM-430	T114−3d	10-Nov-2015 02:59	−142.00	292.74	...	...	...	*CANCELLED*	...	...	
Titan-114 (T114): 13-Nov-2015 05:47:39 ET, Altitude= 11920 km, Flyby ΔV= 226.6 m/s, 36.5 days to E22, $\Delta(\mathbf{B}\cdot\mathbf{R}, \mathbf{B}\cdot\mathbf{T}) = (0.0, -5.0)$ km											
OTM-431	T114+3d	16-Nov-2015 02:29	172.67	984.14	0.104	220.07	14.41	**TBD**	**TBD**	**TBD**	RCS
OTM-432	∼apo	26-Nov-2015 02:13	154.90	641.50	...	...	...	*CANCELLED*	...	...	
OTM-433	E22−4d	16-Dec-2015 00:44	−166.81	242.83	...	...	...	*CANCELLED*	...	...	
Enceladus-22 (E22): 19-Dec-2015 17:50:23 ET, Altitude= 5000 km, Flyby ΔV= 0.3 m/s, 27.4 days to T115											

* Total $\Delta\mathbf{V}$ is the sum of $\Delta\mathbf{V}$s due to the burn, roll and yaw turns, the pointing-bias-fix turn for MEA burns, and the 5.8 mm/s deadband tightening for RCS burns. Expressed in Earth Mean Equator & Equinox of J2000.0 coordinates (EME2000).

† Target condition(s) changed via maneuver.

Table 2: Maneuver Designs (OTMs 383–433). *Data from executed maneuvers are shaded in gray, and data from main engine maneuver designs are indicated in bold.*

OTM	Prime Maneuver Window						Backup Maneuver Window					
	True Anomaly (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	Burn Time (sec)	True Anomaly (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	Burn Time (sec)
383	127.88	309.72	0.0459	−157.76	−140.75	41.01	135.64	301.97	0.0391	−157.33	−131.51	34.18
384	−168.19	245.84	0.0027	92.31	−47.63	3.05	−163.86	241.52	0.0030	90.27	−43.47	3.37
385	−34.88	112.62	0.0322	−110.40	−68.51	27.37	7.77	69.96	0.0480	−113.87	−76.99	43.54
386	123.24	306.71	0.0307	19.76	−82.21	25.74	131.64	298.33	0.0355	15.81	−82.67	30.60
387	**−151.68**	**221.73**	**12.4598**	**−0.05**	**−109.48**	**70.91**	**−145.99**	**216.05**	**13.0189**	**−0.35**	**−115.34**	**74.09**
388	−35.10	104.86	0.0324	61.41	−122.69	27.45	−7.71	77.47	0.0505	76.31	−134.88	45.87
389	134.92	310.65	0.0158	−147.83	−100.49	10.56	141.64	303.94	0.0177	−150.39	−106.40	12.51
390	**−167.95**	**253.56**	**1.2659**	**110.83**	**−136.11**	**7.38**	**−163.94**	**249.57**	**1.2599**	**110.94**	**−140.01**	**7.35**
391	−37.80	123.44	0.0837	−28.64	−115.58	79.37	12.26	73.38	0.1299	−40.34	−93.34	125.92
392	141.29	315.98	0.0664	−166.48	−78.79	61.94	147.05	310.23	0.0769	−168.99	−71.74	72.48
393	**−169.51**	**266.82**	**1.0647**	**40.55**	**−20.89**	**6.18**	**−166.05**	**263.37**	**1.0625**	**39.12**	**−17.36**	**6.17**
394	−46.70	144.03	0.0357	137.85	−65.38	30.70	17.33	79.98	0.0536	107.76	−81.94	48.77
395	135.09	320.33	0.0623	105.75	−97.74	57.82	140.18	315.26	0.0686	103.84	−94.56	64.26
396	−167.65	263.10	0.1975	−88.59	−62.05	194.83	−165.72	261.17	0.2010	−89.51	−64.30	198.33
397*	−67.33	162.81	0.0371	−177.39	−117.23	32.38	−8.28	103.75	0.0282	−84.99	−119.52	23.26
398	144.70	329.29	0.1612	−125.64	−101.92	158.67	149.98	324.01	0.1752	−131.21	−102.11	172.91
399	**−166.54**	**280.58**	**0.9683**	**−101.32**	**−17.27**	**5.61**	**−163.56**	**277.60**	**0.9672**	**−106.24**	**−17.82**	**5.60**
400	−72.18	186.18	0.1632	−138.60	−52.15	160.41	23.14	90.83	0.0555	−12.64	−77.80	51.19
401	148.51	331.96	0.2289	−123.95	−133.44	227.48	153.21	327.28	0.2187	−137.91	−129.74	217.09
402	**−165.55**	**286.08**	**1.2677**	**−31.72**	**−31.09**	**7.34**	**−162.71**	**283.23**	**1.2923**	**−32.19**	**−32.24**	**7.48**
403	−86.11	206.59	0.0293	159.97	−174.58	24.58	23.61	96.85	0.0753	−94.80	−117.56	71.76
404	**150.63**	**333.52**	**0.4971**	**−159.93**	**−151.06**	**2.96**	**154.99**	**329.16**	**0.5735**	**−165.31**	**−149.44**	**3.42**
405	−166.58	290.77	0.0996	135.24	−89.72	96.81	−163.94	288.13	0.1165	135.48	−90.44	114.14
406*	−93.80	217.94	0.0228	104.32	−133.73	18.05	34.21	89.87	0.0193	35.84	−127.24	14.46
407	154.21	438.91	0.0166	−66.94	−128.14	11.56	158.46	434.68	0.0150	−67.48	−131.17	9.94
408	167.67	65.43	0.0470	−57.76	−131.16	43.24	170.34	62.76	0.0469	−57.57	−131.31	43.16
409*	−154.30	27.43	0.0181	−49.75	−102.70	13.17	−149.05	22.19	0.0175	−44.29	−96.01	12.56
410	140.16	656.09	0.0610	−18.49	−22.38	57.68	150.73	645.52	0.0743	−44.39	−33.23	71.48
411	−175.08	251.19	0.0599	−55.88	−108.82	56.56	−171.55	247.67	0.0720	−55.36	−103.36	69.06
412*	−151.66	227.76	0.0186	110.16	−111.14	13.70	−141.75	217.85	0.0221	104.10	−96.82	17.33
413	158.18	342.08	0.0185	−78.73	−51.35	13.63	163.35	336.91	0.0175	−92.59	−64.42	12.55
414	−178.38	318.67	0.0704	86.33	−124.24	67.25	−175.02	315.32	0.0760	89.82	−117.13	73.05
415	−122.11	262.39	0.0017	91.82	−43.50	2.07	−0.33	140.53	0.0042	−29.91	−71.87	4.74
416	159.74	497.05	0.0960	115.57	−31.61	93.55	164.04	492.76	0.0909	108.30	−28.72	88.38
417	−173.35	110.04	0.0181	−47.48	−88.84	13.17	−170.16	106.86	0.0227	−48.27	−85.68	17.96
418	−152.61	89.32	0.0019	−85.88	−82.13	2.25	−144.91	81.61	0.0030	−86.33	−87.21	3.49
419	149.62	436.12	0.0581	19.77	−20.84	54.88	155.93	429.81	0.0644	−5.75	−22.01	61.35
420	−97.38	323.15	0.0009	129.67	−139.80	1.22	76.32	149.31	0.0012	85.38	−62.65	1.51
421	−161.87	27.51	0.0222	−40.77	−69.19	17.40	−157.15	22.81	0.0330	−42.49	−67.91	28.59
422	**146.47**	**148.98**	**0.2521**	**135.01**	**−172.03**	**1.51**	**157.28**	**138.17**	**0.3614**	**72.87**	**−157.15**	**2.16**
423	**174.06**	**121.39**	**2.6256**	**29.67**	**−116.00**	**15.00**	**178.26**	**117.18**	**2.4582**	**29.39**	**−116.35**	**14.04**
424	−163.26	98.71	0.0345	−41.51	−100.18	30.40	−155.95	91.41	0.0594	−45.78	−97.83	56.39
426	174.31	251.04	0.0704	−71.91	−47.58	67.80	178.46	246.89	0.0827	−77.43	−54.75	80.62
427	−162.90	228.25	0.0067	109.67	−127.90	7.40	−155.54	220.89	0.0088	103.43	−116.92	9.54
428	124.45	386.29	0.0149	−51.85	−146.29	9.84	148.09	362.65	0.0311	−55.08	−147.02	26.72
429	−177.12	327.87	0.1108	85.02	−104.02	109.50	−172.89	323.63	0.1362	82.64	−99.93	135.73
430	−142.00	292.74	0.0053	−24.48	−52.61	5.91	−92.82	243.58	0.0098	−90.23	−27.87	10.59
431	172.67	984.14	0.1036	−89.92	−138.60	101.79	177.16	979.66	0.0969	−85.38	−135.71	94.82
432	154.90	641.50	0.0046	174.39	−139.24	5.19	163.04	633.36	0.0041	148.14	−140.26	4.71
433*	−166.81	242.83	0.0154	−44.85	−59.12	10.47	−160.23	236.27	0.0227	−49.37	−69.71	18.11

* Prime and backup maneuver designs required time-of-flight modifications to make implementable.

Table 3: Targeted Encounter History (Titan-102 to Enceladus-22)

Encounter	Flyby Characteristics				Reference Trajectory Target Conditions (Earth Mean Orbital Plane & Equinox of J2000.0)				Flyby Differences from Reference Trajectory		
	In/ Out*	V_∞ (km/s)	Period (days)	Inc. (deg)	$\mathbf{B}\cdot\mathbf{R}$ (km)	$\mathbf{B}\cdot\mathbf{T}$ (km)	TCA (ET SCET)	Alt.† (km)	$\Delta\mathbf{B}\cdot\mathbf{R}$ (km)	$\Delta\mathbf{B}\cdot\mathbf{T}$ (km)	ΔTCA (sec)
Titan-102	Out	5.36	31.9	46.5	2802.59	−5907.25	18-Jun-2014 13:29:32	3659	−0.30	−0.12	−0.04
Titan-103	Out	5.39	32.0	48.0	2270.82	−7654.82	20-Jul-2014 10:42:05	5103	0.15	−0.05	7E−04
Titan-104	Out	5.39	31.9	44.6	−741.35	3763.50	21-Aug-2014 08:10:16	964	−0.03	0.07	−5E−03
Titan-105‡	Out	5.39	31.9	40.3	−2011.39	3769.93	22-Sep-2014 05:24:26	1400	−1.19 *(−1.0)*	0.93 *(+1.0)*	−0.05
Titan-106	Out	5.38	47.9	33.1	−649.36	3829.79	24-Oct-2014 02:41:37	1013	8E−03	0.07	3E−03
Titan-107‡	Out	5.38	31.9	28.7	−3823.78	473.77	10-Dec-2014 22:27:42	980	−0.23	0.07	0.42 *(+0.4)*
Titan-108	Out	5.38	31.9	19.1	−3194.43	2135.11	11-Jan-2015 19:49:42	970	−0.11	−0.18	2E−03
Titan-109	Out	5.38	31.9	8.5	−3620.19	1866.37	12-Feb-2015 17:09:11	1200	−0.44	−1.69	0.06
Titan-110‡	Out	5.38	28.1	0.3	−5102.76	700.16	16-Mar-2015 14:30:56	2275	0.04	0.05	−0.66 *(−0.7)*
Titan-111‡	In	5.38	18.9	0.3	2700.26	4903.33	07-May-2015 22:51:31	2721	0.46	0.31	−0.79 *(−0.7)*
Dione-4§	Out	7.31	19.0	0.4	−872.81	632.83	16-Jun-2015 20:12:59	517	−0.92	−0.90	−0.12
Titan-112§	Out	5.47	21.8	0.5	3539.80	13363.96	07-Jul-2015 08:10:58	10953	−0.25	−0.59	5E−03
Dione-5§	In	6.43	21.9	0.4	−1009.06	256.69	17-Aug-2015 18:34:33	479	0.21	−0.63	0.06
Titan-113	In	5.40	13.9	0.6	1841.27	3445.51	28-Sep-2015 21:38:20	1036	−0.15	−0.06	−0.04
Enceladus-20	In	8.51	13.9	0.6	−1895.43	888.65	14-Oct-2015 10:42:37	1846	−0.09	−1.67	0.24
Enceladus-21§	Out	8.49	13.9	0.6	262.88	−139.07	28-Oct-2015 15:23:50	50	**TBD**	**TBD**	**TBD**
Titan-114‡,§	Out	5.35	12.7	1.4	2663.63	−14563.62	13-Nov-2015 05:47:39	11920	**TBD**	**TBD** *(−5.0)*	**TBD**
Enceladus-22§	Out	9.54	12.9	1.3	4902.46	−1871.06	19-Dec-2015 17:50:24	5000	**TBD**	**TBD**	**TBD**

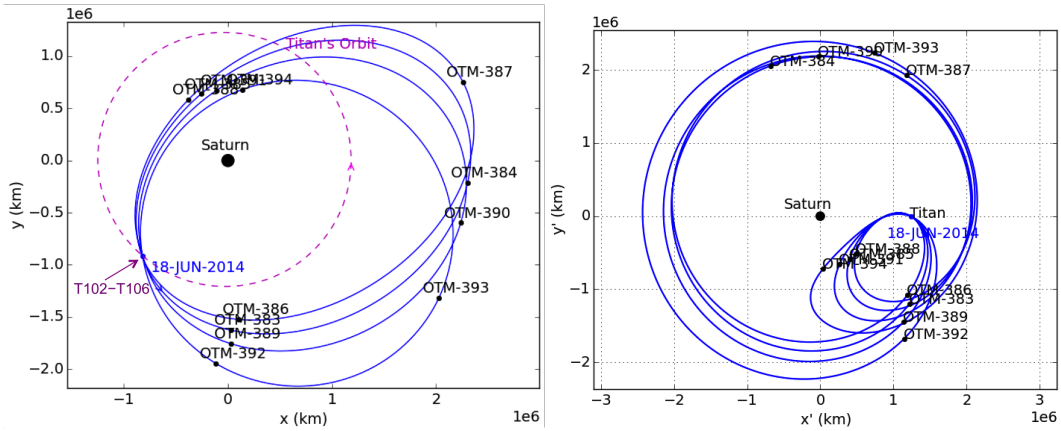
* An inbound encounter occurs before pericrone (Saturn periapsis). An outbound flyby occurs after pericrone.
† Flyby altitudes not explicitly targeted by maneuvers; reported altitudes from reference trajectory (relative to sphere).
‡ Target condition(s) changed via maneuver; the quantities in parentheses denote differences from reference trajectory.
§ Flyby differences may appear large due to cancelled maneuver(s).

of Enceladus and Dione, and the beginning of **In-3**, up to the last Enceladus targeted flyby of the mission. The following subsections describe the maneuvers during this time frame, grouped by targeted encounter, and the maneuvers of interest are highlighted.

Titan Occultation and Inclination Reduction Sub-Phase (In-2C)

Titan-102 to Titan-106: 2:1 Resonant Transfers The set of Cassini's 2:1 resonant transfers from T102 on 18-June-2014 to T106 on 24-Oct-2014 is shown in Figure 7. The Saturn-centered inertial J2000 view is in Figure 7(a) and the Saturn-Titan rotating coordinate frame is in 7(b). The black dots along the transfer orbit represent the location of the planned OTMs. The x'-axis of the rotating frame is parallel to the line connecting Saturn and Titan. The z'-axis is along the angular momentum vector of the system and y' completes the right-handed frame. An apparent 'loop' is seen in the trajectory in Figure 7(b), a typical characteristic of resonant transfers as seen in a rotating frame. In an n:m resonant transfer, n represents the number of revolutions of Titan around Saturn, whereas m determines the number of passages through periapses. In exterior resonant orbits (where $n > m$), the spacecraft travels in opposite direction in the rotating frame than it does in an inertial frame, since its period is larger than Titan's period. The loops occur when the spacecraft approaches periapsis and it momentarily travels faster around Saturn than Titan.[8]

After the Titan-102 flyby, the cleanup maneuver OTM-383 (RCS) was designed to directly target



(a) Saturn Centered Inertial J2000 View

(b) Saturn-Titan Rotating View

Figure 7: Cassini's 2:1 resonant trajectory from 18-June-2014 to 24-Oct-2014.

Titan-103 (leaving OTM-384 as a statistical maneuver). This was decided because the savings to perform a chained optimization with OTM-384 were minimal (only 20 mm/s). Also, the apoapsis maneuver would have required a ΔV increase to make it implementable, therefore removing any acquired savings. OTM-384 was then cancelled since it was too small to implement at 2.7 mm/s, and the the spacecraft was within 5 km of the flyby target with an error ellipse less than 3 km at the time of the data cutoff. Once closer to the T103 target, the orbit determination (OD) uncertainties reduced, and Cassini was further from the target than expected. Therefore, the approach maneuver OTM-385 (RCS) was performed with a ΔV of 32.2 mm/s. This was a necessary maneuver, since there would be a 0.46 m/s downstream penalty cost if the maneuver had not been performed.

Because the Titan-103 target was only missed by 200 m, the cleanup maneuver OTM-386 was cancelled (the downstream penalty cost for canceling was only 35 mm/s). The apoapsis maneuver OTM-387 was the last planned main engine maneuver over 10 m/s of the mission. With such a large planned maneuver, an Operational Ready Test (ORT) was performed to be prepared to finish the maneuver on RCS thrusters if MEA fuel ran out before completing the burn. In such a case, there would not be enough RCS fuel to finish the mission, and a contingency plan would be set in place to safely dispose of the spacecraft and meet all planetary protection requirements.[11] The T104 approach maneuver OTM-388 ΔV was 32.4 mm/s. Even though it was a small maneuver, the penalty cost for cancelling would be over 3.5 m/s, mostly observed in OTMs-389 and 390, which would cause the Titan-104 flyby to be off by more than

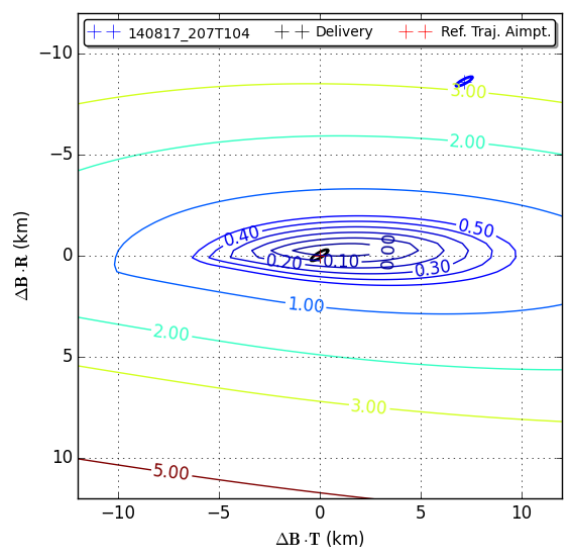


Figure 8: T104 Cost Contours (OTM-388)

10 km (blue ellipse in Figure 8). The contour plot is a two-dimensional linear representation of a larger six-dimensional solution, displaying ΔV costs for different B-plane encounter positions of the spacecraft with respect to the nominal B-plane encounter aimpoint (located at the origin). The maneuver delivery ellipse is represented in black and the orbit determination ellipse in blue (this is the spacecraft's location had the maneuver been canceled). The plots are generated using a linear analysis tool, which produces ΔV statistics by simulating the execution of a sequence of maneuvers through a Monte Carlo process. OTM-388 was an extremely accurate maneuver, causing the Titan-104 flyby to be one of the most accurate flybys of the mission, being off by only 98 m.

The next cleanup maneuver (OTM-389) was also cancelled due to a small, almost negligible, cancelation cost. This decision to cancel the maneuver had the added bonus that the deviations from the reference trajectory decreased. OTM-390 (MEA) was performed at 1.27 m/s, with a large penalty cost of 43 m/s had the maneuver not been performed. By altering the T105 B-plane aimpoint coordinates by -1 km in $\mathbf{B} \cdot \mathbf{R}$ and +1 km in $\mathbf{B} \cdot \mathbf{T}$ via OTM-391, an additional 0.16 m/s downstream ΔV was saved. The following three maneuvers (OTMs 392–394) were all performed, giving a miss of only 110 m at the Titan-106 flyby.

Titan-106 to Titan-107: 3:1 Resonant Transfer The T106 flyby increased the spacecraft's period to 48 days, yielding a 3:1 resonant transfer to T107 (plotted in Figure 10). The maneuvers between this encounter were all performed as RCS, with a large apocrone maneuver of 0.197 m/s. The approach maneuver, OTM-397, was initially too small to implement at 6.4 mm/s; however, the ΔV penalty cost for canceling was deemed too high at 0.2 m/s. The decision was made to change the flyby encounter time at T107 in order to make OTM-397 large enough to be implemented. Figure 9 shows the maneuver magnitude as a function of the time-of-flight (TF) change necessary to make the ΔV of implementable size (15.8 mm/s including the ΔV for deadband-tightening). The two solutions that result in a ΔV that meets the minimum requirement are labeled in the plot. Notice that the required shift in time is extremely small (less than one second). In general, both positive and negative TF shift solutions are considered, and a final decision is based on downstream ΔV costs, acceptable reaction wheel speeds determined by the attitude control team, and minimum disruption to the science team for data measurements. The original TF bias was chosen at +0.3 s, but this resulted in a 180° roll turn, which is undesirable. The final TF bias was chosen at +0.4 s, with a ΔV of 37.1 mm/s. This was also the first time doing a maneuver only four days after solar conjunction, and resulted in a 240 m miss at the Titan-107 encounter.

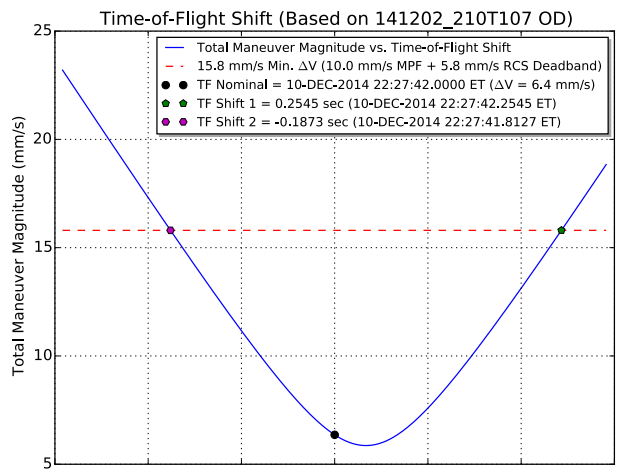
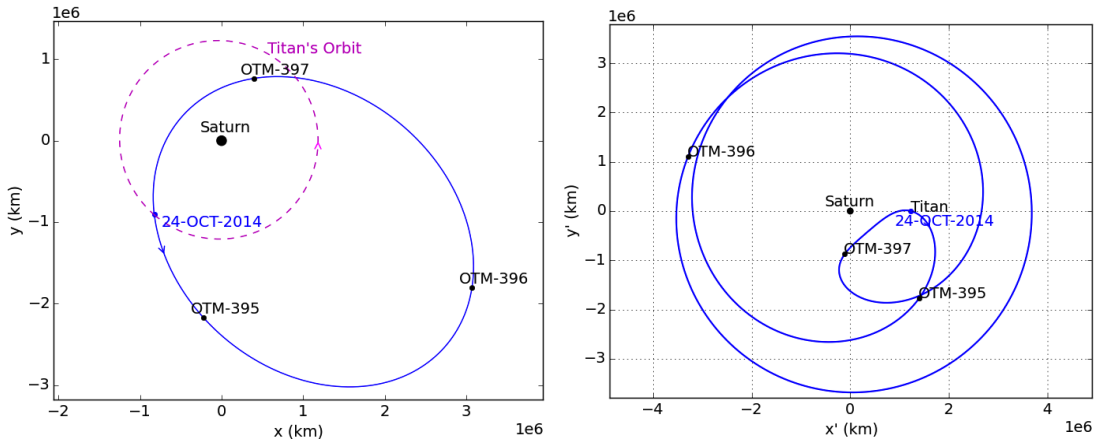


Figure 9: Time-of-flight bias for Titan-107

Titan-107 to Titan-109: 2:1 Resonant Transfer The Titan-107 flyby reduced the spacecraft's period to 32 days, to allow a 2:1 resonant transfer for the following two encounters. The trajectory for this transfer in an inertial and rotating frame is shown in Figure 11. The following two maneuvers

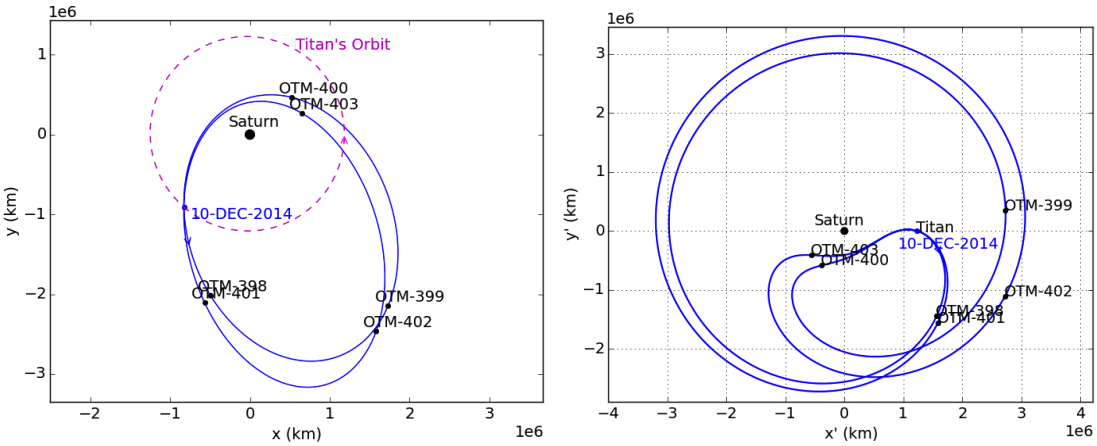


(a) Saturn Centered Inertial J2000 View

(b) Saturn-Titan Rotating View

Figure 10: Cassini's 3:1 resonant trajectory from 24-Oct-2014 to 10-Dec-2014.

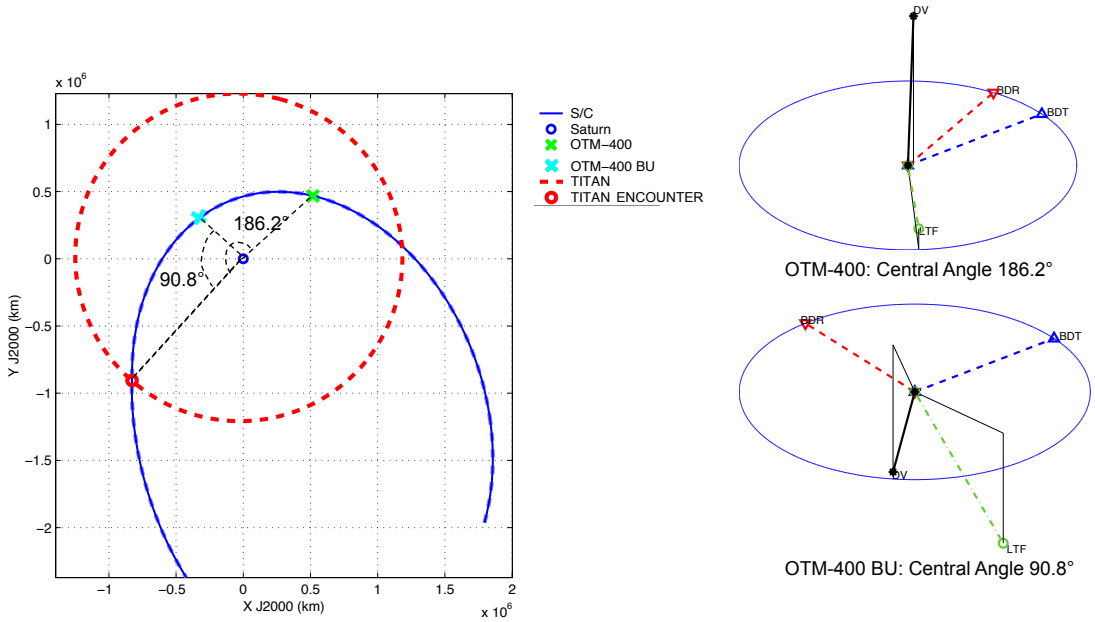
after T107 were performed, with the cleanup maneuver (OTM-398) as a large RCS burn at 0.162 m/s and the apocrone maneuver (OTM-399) as a main engine burn at 0.97 m/s. The ΔV magnitude for the approach maneuver (OTM-400) at the prime window was three times larger than at the backup opportunity, at 0.163 m/s versus 0.052 m/s. Also, the central angle (angle between the maneuver and the encounter location) for the prime window was $186.2°$ (Figure 12(a)), which is near the $180°$ singularity point. Here, the gradients $\nabla(\mathbf{B} \cdot \mathbf{R})$, $\nabla(\mathbf{B} \cdot \mathbf{T})$, and $\nabla(\mathrm{TF})$ become co-planar (Figure 12(b)), and the inverse of the targeting matrix $\mathbf{K}$ (Eq. (2) in Appendix) used to compute the required ΔV becomes singular, making the maneuver solution extremely unstable (see Appendix for more details). On the other hand, the central angle for the backup maneuver was $90.8°$, making the solution much more stable. Therefore, the maneuver was implemented at the backup opportunity (OTM-400 BU).



(a) Saturn Centered Inertial J2000 View

(b) Saturn-Titan Rotating View

Figure 11: Cassini's 2:1 resonant trajectory from 10-Dec-2014 to 12-Feb-2015.



(a) OTM-400 and OTM-400 BU maneuver locations on trajectory

(b) Gradients $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and TF for prime and backup opportunities

Figure 12: Approach maneuver OTM-400 for T108 encounter: prime and backup solutions.

For the 2:1 resonance to be maintained, the period before and after Titan-108 had to remain constant; however, the flyby reduced the orbital inclination. These orbital elements are plotted in the B-plane of the encounter in Figure 13, where the red circle represents Titan and the black square is the encounter location. The orbital period is approximately 32 days after the flyby (top-left), and the change in the period is negligible (bottom-left); the orbital inclination is 19.1° (top-right), with a reduction in inclination of 9.54° (bottom-right). These values are computed using two-body approximation equations and are useful for preliminary mission design purposes to determine the desired location of the encounter on the B-plane. The incoming asymptote (i.e. $\mathbf{v}_\infty$) determines the orbital elements before the encounter. However, depending on where the $\mathbf{v}_\infty$ pierces the B-plane, different outgoing orbital elements will be achieved, which are represented in Figure 13 for all the possible B-plane encounter positions around Titan. There is a clear asymptote in the period change plot where the encounter had to occur for the period to be kept constant (0.00 line). Similarly, in the inclination change plot, there is an asymptote that results in no inclination change (0.00 line): any encounter to the right of this line reduces inclination, and to the left increases inclination. The encounter location for T108 was strategically chosen to maintain the period and obtain a large reduction in inclination in preparation for the next equatorial phase.

After the T108 flyby, OTM-401 was performed as an RCS maneuver at 0.229 m/s, which is the largest RCS burn on the B-branch set of thrusters to date. OTM-402 was a must-do main engine maneuver at 1.27 m/s, with a ΔV downstream penalty cost of 16.8 m/s had the maneuver not been performed. OTM-403 was a 30 mm/s RCS maneuver, with the largest yaw turn to-date at 174.6°.

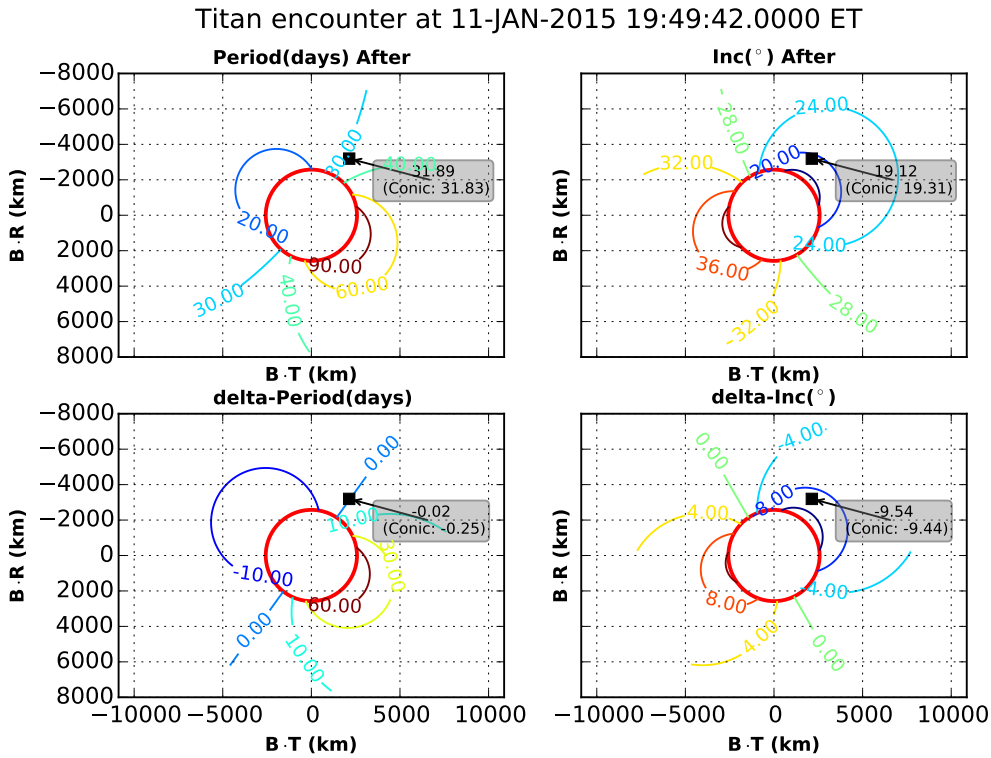


Figure 13: Titan-108 Encounter Orbital Element Change in Period and Inclination. Period (top-left) and inclination (top-right) after the flyby. Change in the period (bottom-left) and change in inclination (bottom-right) due to the flyby.

Second Equatorial Phase (Eq-2)

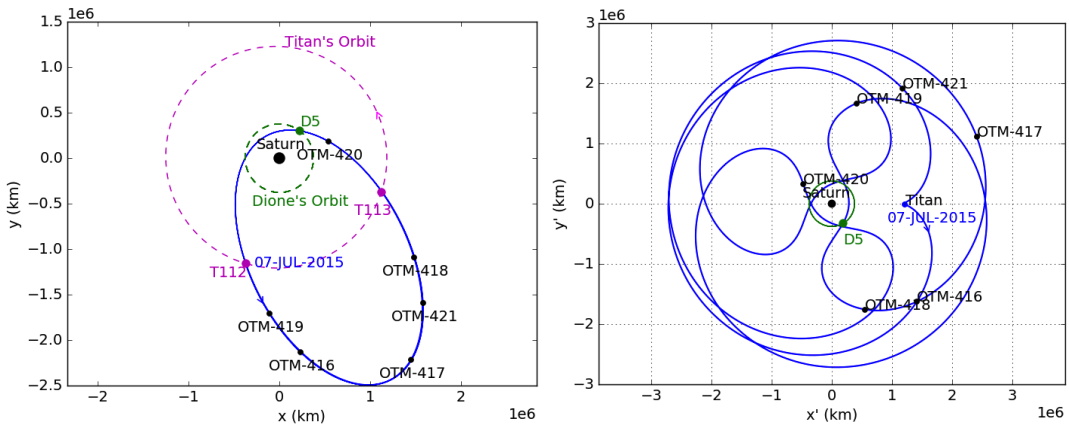
The Eq-2 Phase spans four Titan flybys (T110-T113), two Dione flybys (D4, D5), and two Enceladus flybys (E20, E21), in which the inclination of Cassini's orbit is near zero. OTM-404 (RCS) was optimized together with OTM-405 (MEA) to target T110. The approach maneuver OTM-406 (RCS) required a TF bias of -0.7 s in order to make the maneuver magnitude large enough to be implementable. At the closest approach, there was a temporary swap from the high-gain antenna (HGA) to low-gain antenna (LGA) for radio science. OTM-406 was a high priority maneuver to perform, because of the risk of not being able to execute OTM-407 had the spacecraft not switched back to HGA after the flyby. The T110 flyby was accurate enough and OTM-407 was cancelled. OTM-408 (RCS) targeted the T111 encounter and, as in the previous approach maneuver, OTM-409 (RCS) required a TF bias. Both the positive and negative TF bias options were studied, but due to better wheel speeds for attitude control, the negative TF bias option was executed, at -0.7s TF bias for the prime and -0.3 s for the backup maneuver opportunities.

The 2,700 km flyby at T111 had a 580 m miss. The cleanup maneuver OTM-410 was larger than expected due to the 1-1/2 sigma OD movement from the flyby and periapsis passage. OTM-411 (RCS) had a slight over burn, which allowed the approach maneuver to D4, OTM-412, to

be cancelled. The previous Dione targeted encountered had occurred almost four years prior to D4; therefore, the knowledge of Dione's orbit had a big uncertainty at the time of the flyby. Even though D4 flyby had an 800 m miss, OTM-413 was cancelled, since the downstream cost of cancellation was only 20 mm/s. OTM-414 (RCS) had an accurate execution, which allowed OTM-415, the approach maneuver for T112, to be cancelled.

The trajectory from T112 through D5, up to T113 is shown in Figure 14 in both an inertial and rotating frame. OTM-416 (RCS) was designed to target directly to D5, since the savings in doing a two-maneuver optimization with OTM-417 was negligible. The apocrone maneuver was left as a statistical maneuver, but due to execution errors in OTM-416, OTM-417 (RCS) was executed. This maneuver required a close to 90° yaw turn. At the data cutoff time for OTM-418, the OD team determined Cassini was 700 m from the target, with an even larger semi-major axis uncertainty, calling into question the benefit of performing a correction maneuver. A target TF bias of +0.8 seconds was required to make OTM-418 large enough to be implementable, which translated to an offset of 5 km from the reference target, nearly an order of magnitude larger than the target miss realized by canceling the maneuver. For these reasons, OTM-418 was cancelled.

After the D5 flyby, the cleanup maneuver OTM-419 (RCS) was designed to target directly to the T113 target. This was designated a must-do maneuver because of the 100% impact probability with Titan had the maneuver not been performed. The option of performing a two-maneuver optimization with OTM-420 was considered, but the ΔV savings were negligible. When the time came to design OTM-420, it was too small to execute; therefore, the maneuver was cancelled. OTM-421 was performed nominally to target the T113 flyby. Even though the maneuver was only 22 mm/s, the cancellation cost grew to 3 m/s, re-iterating the importance of executing every necessary maneuver to save fuel in the long run.



(a) Saturn Centered Inertial J2000 View

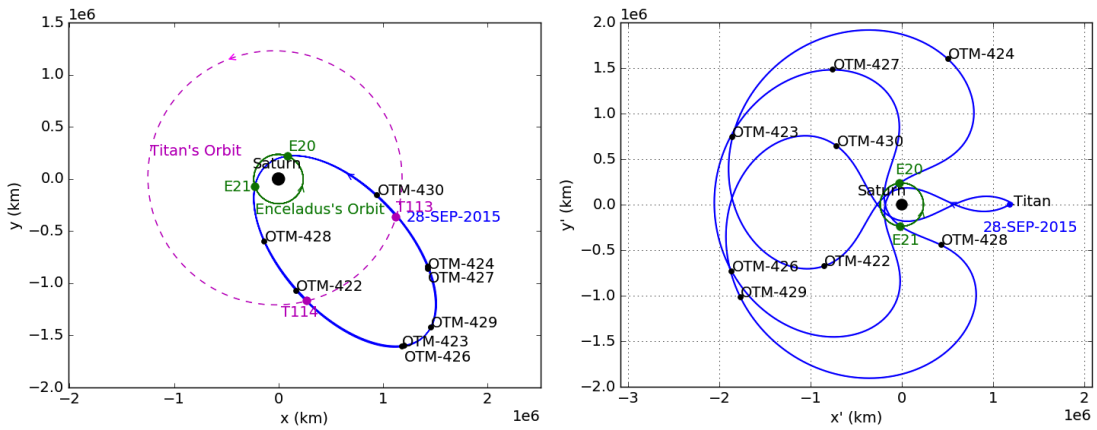
(b) Saturn-Titan Rotating View

Figure 14: Cassini's trajectory from 7-Jul-2015 to 28-Sep-2015.

The trajectory from T113 to T114, including E20 and E21, is plotted in Figure 15 in an inertial frame (a) and rotating frame (b). After T113, OTM-422 (MEA) ΔV was 0.252 m/s, with a burn duration of 1.51 s (second smallest MEA burn performed during the mission). OTM-423 (MEA) targeted the E20 flyby and the approach maneuver OTM-424 (RCS) corrected for execution errors due to the prior maneuver. Even though the cancellation of OTM-424 only showed a 40 mm/s ΔV

penalty downstream, it would have caused Cassini to miss the sunlight as it passed Enceladu's north pole. Since this was the last planned north pole flyby of Enceladus, the maneuver was executed.

To target E21, the closest Cassini has ever flown through the plumes, only one planned maneuver was required. Therefore OTM-425 was designed as a skip maneuver to maintain the OTM numbering scheme. OTM-426 (RCS) was performed at a ΔV of 70.4 mm/s and, since OTM-427 was not big enough to implement, it was cancelled. A TF bias would have created a 1.7 km offset from the reference trajectory, which was nearly 10 times more than the 0.2 km target miss from canceling.



(a) Saturn Centered Inertial J2000 View

(b) Saturn-Titan Rotating View

Figure 15: Cassini's trajectory from 28-Sep-2015 to 13-Nov-2015.

Beginning of the Third Inclined Phase (In-3)

After the E21 flyby, the cleanup maneuver OTM-428 was cancelled since the spacecraft was within half the uncertainty sigma of the E21 target. However, during the design phase, the backup maneuver was going to be implemented, in order to ensure downlink of all the E21 flyby science data during the first pass after the flyby. The B-Plane aimpoint for T114 was changed by +5.0 km in $\mathbf{B} \cdot \mathbf{T}$ (no change in $\mathbf{B} \cdot \mathbf{R}$) during OTM-429 in order to save 70 mm/s downstream. The approach maneuver OTM-430 was too small to implement and had a cancelation cost of only 10 mm/s; therefore, the maneuver was cancelled.

Following the T114 flyby, the cleanup maneuver OTM-431 was designed to directly target E22, the last Enceladus targeted flyby of the mission. The optimal solution, when computed as a two-chain optimization with OTM-432, places all of the ΔV into OTM-431. The apoapsis (OTM-432) and approach (OTM-433) maneuvers were both cancelled. Even if Cassini missed the target of E22 by 10 km, it was known ahead of time that OTM-434 was cancellable due to the small downstream ΔV cost. This was only the second time in the mission that three planned maneuvers were cancelled in a row, the first time occurring in September 2011 with OTMs 288a, 289, and 290.

NAVIGATION COST ANALYSIS

The maneuver performance per flyby is summarized in Table 4. This maneuver performance, represented by the navigation ΔV cost per flyby (last column), is evaluated by comparing the re-

constructed ΔV from each encounter span to the planned ΔV from the reference trajectory (shaded columns).

Table 4: Maneuver Performance per Encounter (T103 – E22)

Encounter Span	Ref. Traj. Det. ΔV (m/s)	Predicted ΔV Statistics Mean (m/s)	1-σ (m/s)	90%* (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Navigation ΔV Cost† (m/s)
T102 – T103	0.007	0.076	0.045	0.141	0.078	0.077	0.070
T103 – T104	12.449	12.592	0.074	12.693	12.492	12.498	0.050
T104 – T105	1.255	1.515	0.158	1.729	1.350	1.347	0.092
T105 – T106	1.085	1.347	0.156	1.566	1.167	1.164	0.078
T106 – T107	0.176	0.501	0.175	0.742	0.297	0.296	0.120
T107 – T108	0.995	1.318	0.144	1.516	1.185	1.181	0.186
T108 – T109	1.273	1.721	0.351	2.091	1.526	1.532	0.258
T109 – T110	0.006	0.490	0.321	0.941	0.619	0.618	0.612
T110 – T111	0.018	0.218	0.147	0.423	0.065	0.065	0.047
T111 – D4	0.006	0.155	0.091	0.278	0.121	0.122	0.116
D4 – T112	0.006	0.103	0.052	0.172	0.070	0.071	0.065
T112 – D5	0.019	0.140	0.078	0.242	0.114	0.114	0.095
D5 – T113	0.013	0.130	0.054	0.204	0.080	0.079	0.065
T113 – E20	2.702	3.082	0.274	3.454	2.912	2.904	0.202
E20 – E21	0.014	0.191	0.116	0.355	0.070	0.071	0.057
E21 – T114‡	0.010	0.326	0.174	0.568	0.111	**TBD**	*0.101*
T114 – E22‡	0.028	0.220	0.135	0.406	0.104	**TBD**	*0.075*

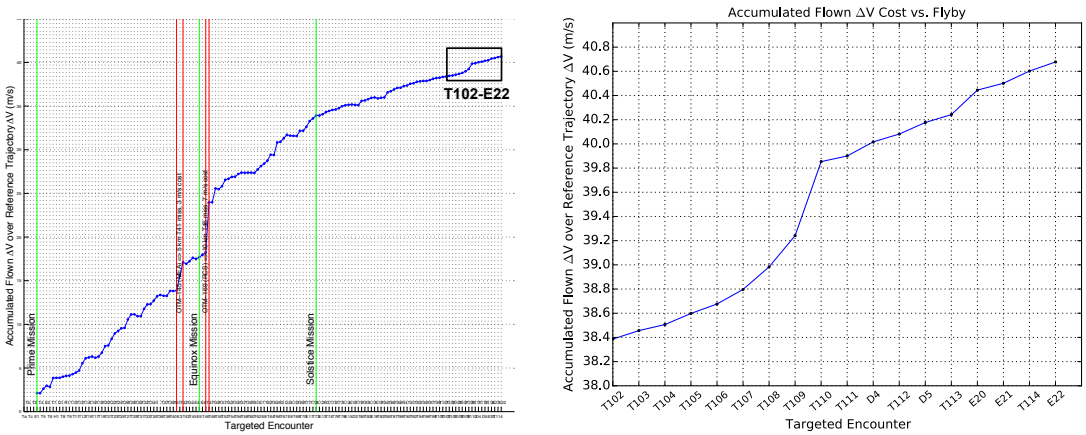
* Total ΔV in encounter span will be less than or equal to this value with a 90% confidence level.
† Navigation ΔV cost = reconstructed ΔV − reference trajectory deterministic ΔV. Note, the computed navigation costs are based on the raw numbers to avoid round-off errors.
‡ Reported navigation cost is based on preliminary orbit determination estimates.

The average navigation ΔV cost per flyby is summarized in Table 5. The cost between each encounter was not as evenly distributed prior to the Solstice Mission, as evidenced by the large standard deviation of nearly 1 m/s for the Equinox Mission. With the majority of the maneuvers performed on RCS during the Solstice Mission, the average navigation cost so far has been less than half the average costs seen in the prior missions.

Figure 16(a) shows the total mission ΔV cost from the beginning of the mission, where it is evident that the slope of the accumulated ΔV has decreased since the start of the Solstice Mission, due in part to the refinements in the maneuver decision process. The ΔV cost of the encounters covered in the scope of this paper (T102 to E22) is shown in Figure 16(b). The 1 km miss at the Titan-109 flyby (the largest miss during this time frame), resulted in an immediate 0.61 m/s navigation cost, even though the deterministic ΔV from the reference trajectory was only 0.006 m/s. This 1 km miss is small in comparison to the 5 km miss during T41 and the 10 km miss during T46, validating the navigation strategy used during the Solstice Mission.

Table 5: Average Navigation ΔV Cost per Encounter. *Average Navigation cost is computed through the first five years of the Solstice Mission.*

Mission	Flyby Span	Number of Flybys	Navigation ΔV Cost	
			Mean (m/s)	Std. Dev. (m/s)
Prime (7/2004 – 9/2008)	Ta – E4	54	0.325	0.594
Equinox (9/2008 – 9/2010)	E5 – T72	36	0.447	0.978
Solstice (9/2010 – 12/2015)	T73 – E22	58	*0.123*	*0.132*



(a) Total Mission ΔV

(b) T102–E22 ΔV

Figure 16: Accumulated Flown ΔV Cost over Reference Trajectory ΔV

CONCLUSION

The fifth year of the Solstice Mission maneuver operations was marked by a high percentage of planned maneuvers cancelled, due in part to the ballistic nature of the trajectory with several icy satellite targeted flybys during this time frame. The navigation strategy is to fly Cassini as close to the reference trajectory as possible. However, as Cassini approaches the 2017 end-of-mission date, preserving propellant is a high priority. Small maneuvers, as well as spacecraft pointing and wheel management, cannot be accomplished via the main engine. Therefore, most opportunities to save small downstream costs have been taken, in the hope that these savings will translate into hydrazine reserves for RCS usage. At the same time, main engine fuel is dwindling, and, with several big deterministic maneuvers still planned, saving bi-propellant is also important. For OTM-438, which will target T116, there is a 1.2% chance that bi-propellant will run out, and a 3.5% chance of this occurring for OTM-444, which will target T118.

In September 2017, Cassini will pass 22 times within a few thousand kilometers of the cloud tops of Saturn, ultimately impacting Saturn. Due to Planetary Protection requirements, the possibility of impact with any large icy moon needs to be prevented if propellant were to run out before the end-of-mission. Several trajectory options are shown in Reference 11 for this scenario. As of January 2016, 18 m/s of usable bi-propellant ΔV is available for main engine maneuvers and 34 m/s of hydrazine is available for RCS maneuvers (at a 90% confidence level). At the end-of-mission, the 90% confidence level studies predict that 23 m/s will be left of hydrazine and all of the bi-propellant will have run out.[12]

APPENDIX: B-PLANE TARGETING

B-plane (Body Plane) targeting is used throughout the entire Cassini tour to target the flyby conditions for each encounter. The B-plane is defined as a plane which is normal to the incoming asymptote of the hyperbolic orbit (i.e., $\mathbf{v}_\infty$), and contains the target body's center of mass. The B-vector is the vector from the target body's center of mass to the point where the $\mathbf{v}_\infty$ vector intersects the B-plane[9] (see Figure 17). This vector can also be defined as the radius of closest approach to the target body, if the target body were massless. Three orthogonal unit vectors are defined with origin at the target body to describe the B-plane: $\hat{\mathbf{S}}$, $\hat{\mathbf{T}}$, and $\hat{\mathbf{R}}$. The $\hat{\mathbf{S}}$ vector is parallel to $\mathbf{v}_\infty$, $\hat{\mathbf{T}}$ is parallel to a convenient reference plane (usually chosen as the ecliptic EMO2000), and $\hat{\mathbf{R}}$ completes an orthogonal triad.

Trajectory errors in the B-plane are characterized by a 1-σ dispersion ellipse, shown in Figure 17, where SMAA is the semi-major axis of the ellipse, SMIA is the semi-minor axis of the ellipse, and θ represents the orientation of the ellipse, measured clockwise from $\hat{\mathbf{T}}$. The dispersion perpendicular to the B-Plane is given as a 1-σ linearized time-of-flight error, where the linearized time-of-flight is the time that the flyby would occur at if the magnitude of the B-vector were zero.

The targeting maneuvers are generally computed using the K-inverse strategy, where three components of the B-plane miss are corrected: $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and TF. The ΔV is computed as

$$\mathbf{\Delta V} = -\mathbf{K}^{-1}\mathbf{\Delta B} \tag{1}$$

where $\mathbf{K}$ is a 3×3 matrix of partial derivatives of the B-plane miss parameters with respect to the spacecraft's velocity

$$\mathbf{K} = \begin{bmatrix} \frac{\delta \mathbf{B}\cdot\mathbf{R}}{\delta V_x} & \frac{\delta \mathbf{B}\cdot\mathbf{R}}{\delta V_y} & \frac{\delta \mathbf{B}\cdot\mathbf{R}}{\delta V_z} \\ \frac{\delta \mathbf{B}\cdot\mathbf{T}}{\delta V_x} & \frac{\delta \mathbf{B}\cdot\mathbf{T}}{\delta V_y} & \frac{\delta \mathbf{B}\cdot\mathbf{T}}{\delta V_z} \\ \frac{\delta TF}{\delta V_x} & \frac{\delta TF}{\delta V_y} & \frac{\delta TF}{\delta V_z} \end{bmatrix} \tag{2}$$

and $\mathbf{\Delta B} = [\ \Delta\mathbf{B} \cdot \mathbf{R}, \Delta\mathbf{B} \cdot \mathbf{R}, \Delta\text{TF}\ ]^T$ is the B-plane error.

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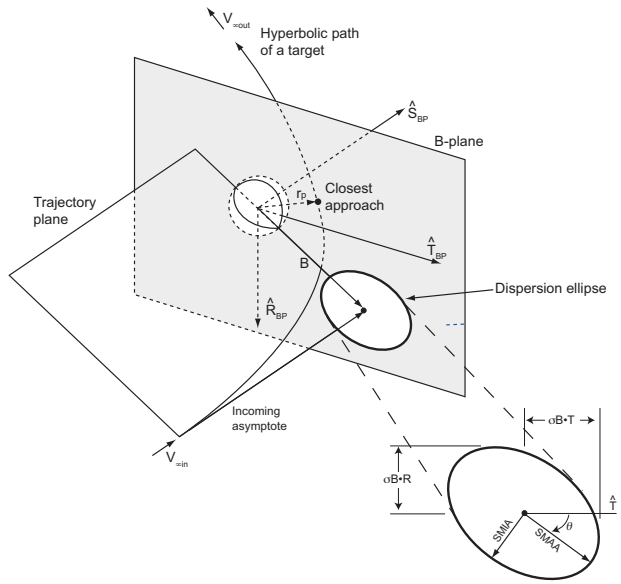

Figure 17: Targeting B-plane Coordinates[13]

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