Cassini Solstice Mission Maneuver Experience: Year Two

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The Cassini Spacecraft was launched in October 1997 on a mission to observe Saturn and its moons; it entered orbit around Saturn in July 2004 for a nominal four-year *Prime Mission*, later augmented by two extensions: the *Equinox Mission*, from July 2008 through September 2010, and the *Solstice Mission*, from October 2010 through September 2017. This paper provides an overview of the maneuver activities from August 2011 through June 2012 which include the design of 38 Orbit Trim Maneuvers—OTM-288 through OTM-326—for attaining 14 natural satellite encounters: seven with Titan, six with Enceladus, and one with Dione.

I. Introduction

The Cassini Spacecraft was launched in October 1997 on a mission to observe Saturn and its moons; it entered orbit around Saturn in July 2004 for a nominal four-year *Prime Mission*, during which the Huygens Probe was released from the spacecraft for a successful landing on Titan. The Prime Mission was augmented by two extensions: the *Equinox Mission*, from July 2008 through September 2010, and the *Solstice Mission*, from October 2010, and expected to last until September 2017.

Earlier papers from the Cassini Maneuver Team reported on the maneuver experience during Cassini's interplanetary cruise to Saturn,[1,2,3] the four years of the Prime Mission,[4,5,6,7] the two years of the Equinox Mission,[8,9,10] and the first year of the Solstice Mission.[10] This paper provides an overview of the maneuver activities during the second year of the Solstice Mission, from August 2011 through June 2012, which include the design of 38 Orbit Trim Maneuvers—OTM-288 through OTM-326—for attaining 14 natural satellite encounters: seven with Titan, six with Enceladus, and one with Dione.

The period under consideration falls into the second half of the *first equatorial phase* (**Eq-1**), and the start of the *second inclined phase* (**In-2**) of the Solstice Mission. During **Eq-1** the line of nodes is rotated towards the Saturn-Sun line using non-resonant transfers; this orbital geometry enables observations of Saturn unobscured by the rings, Saturn high-latitude occultations, and multiple encounters with the icy moons. The rotation of the line of nodes is also necessary to achieve Saturn ring occultations during **In-2**.

The *petal* and *orbital elements* plots presented in Figure 1 depict the spacecraft trajectory as viewed from Saturn's north pole, with the Sun direction along the horizontal axis, and the time profile of orbital inclination and orbital period, from which it is possible to determine the orbital effect of each flyby: the $T87$ flyby provides the period reduction required to attain resonant (13:1) Enceladus transfers $E14$ though $E16$, and enable the double flyby $D3/T79$. The slight inclination during the non-resonant titan transfers $T79$ to $T82$ enables high altitudes and latitudes—more than 30,000 km at over 60° South—important for scientific observations of Titan. $T82$ provides the period reduction required to achieve another three resonant (13:1) Enceladus transfers ($E17$ to $E19$). Finally, the transition from **Eq-1** to **In-2** is enabled by the resonant $T83$ and $T84$ flybys, which together provide a change in orbital inclination of more than 20 degrees. The *orbital events diagram* presented in Figure 2 separates the trajectory into independent revolutions around Saturn

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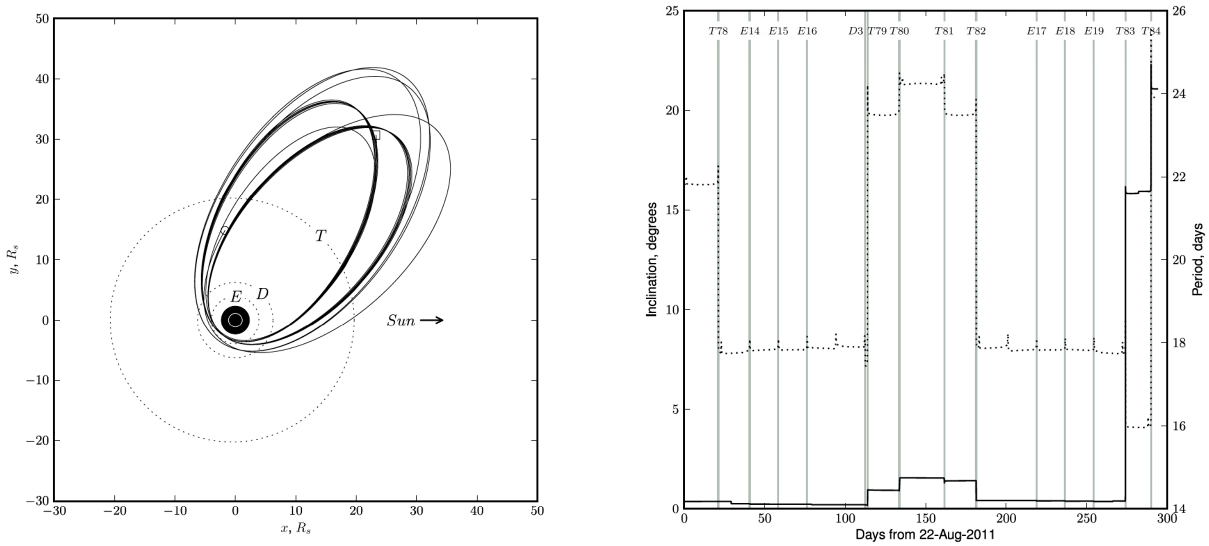

Figure 1. (Left) Cassini's trajectory from Aug-22-2011 (◯) to Jun-11-2012 (□) as viewed from Saturn's north pole, and outlining the orbits of Titan (T), Dione (D), and Enceladus (E); Saturn and the rings are shown to scale; the Sun is to the right of the diagram; the unit distance $R_s = 60,330$ km: the equatorial radius of Saturn at 0.1 bar atmospheric pressure. (Right) the instantaneous orbital inclination with respect to Saturn's true equator (solid line, left axis) and orbital period (dotted line; right axis). Encounters are labeled at the top to highlight the effect of each flyby on the orbital parameters.

(counted from apoapsis to apoapsis); the revolution number is the incremental count from the start of the Mission, the period is the time elapsed between apoapses, and the horizontal line spans the 360 degrees of true anomaly contained in one revolution; each *orbital event* is located in its corresponding revolution and true anomaly. This diagram highlights three major challenges:

Fast orbits After an operational relief granted by revolutions 150, 151, and 153, the maneuver activities resumed with full force: the Navigation team entered into a period of constant turnaround of analyses and designs. Orbits as fast as 17.8 days with three maneuvers and one encounter required a constant pipeline of orbit determinations, maneuver designs, and approval meetings, occasionally on the same working day.

Maneuvers at periapsis OTM-300 and OTM-312 were sizable main engine maneuvers located near periapsis. A naïve placement of their corresponding backup twenty-four hours after their nominal location would have lead to unacceptably large Δv penalties: the spacecraft moves too far away from periapsis in that time period. Instead, the Navigation team prepared contingency scenarios should the prime maneuvers fail to execute due to spacecraft safing.

Double flyby The double flyby in revolution 158 was particularly challenging because the ephemeris uncertainty for the first body, Dione, implied dispersion at Titan as a matter of fact.

In the next sections we provide an overview of the general navigation strategy used by the Maneuver Team, the characteristics of the targeted encounters for this time period, a narrative of the navigation activities for each encounter, and conclude with an assessment of the navigation performance, a summary of the scheduled maneuvers, and the overall maneuver history table.

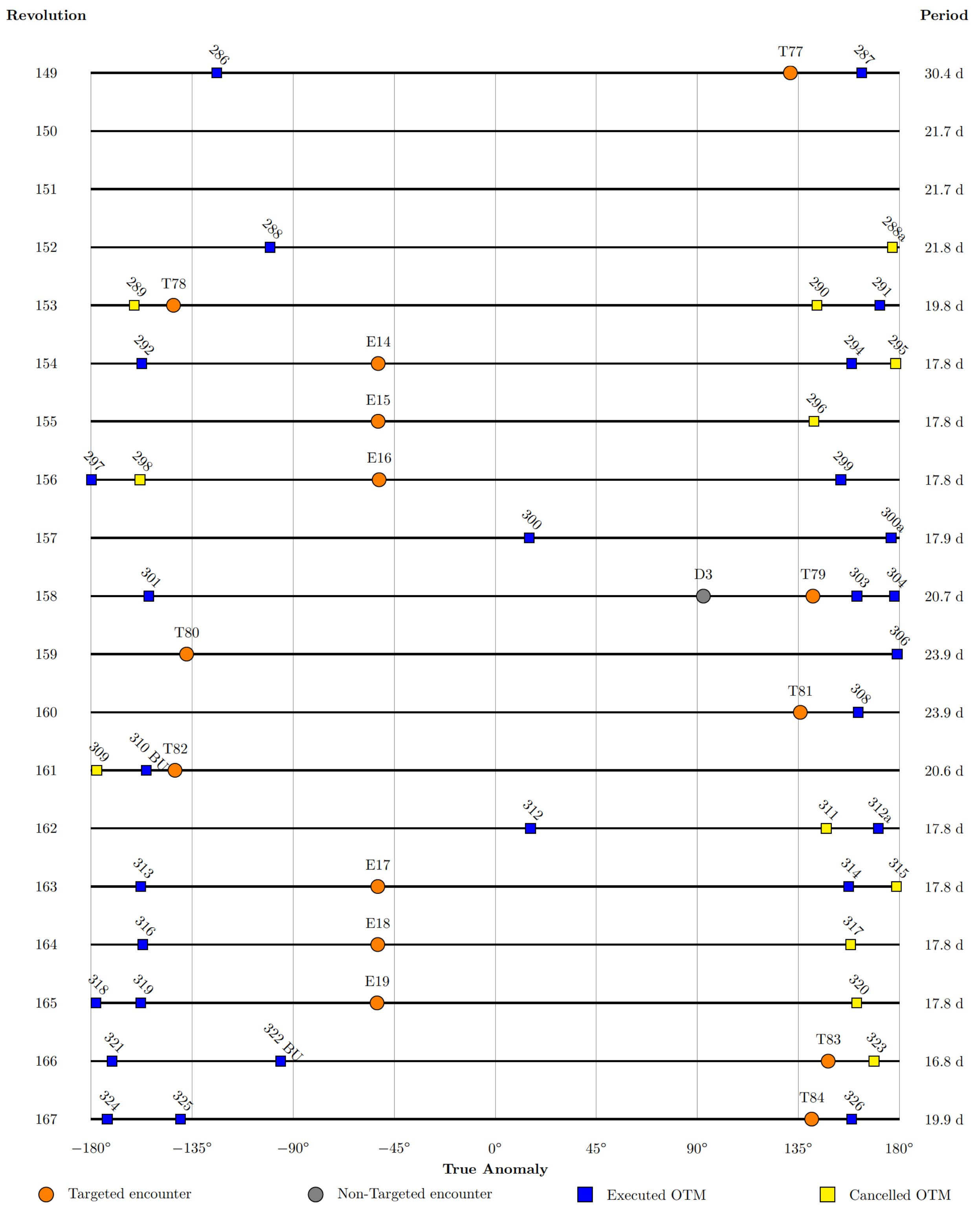

Figure 2. Orbital events diagram for the period under consideration. Each row corresponds to one revolution around Saturn; each revolution is numbered, and its anomalistic period is listed in days (time elapsed between two consecutive passes through apoapsis). One revolution spans 360 degrees of true anomaly (the horizontal axis), negative from apoapsis (180 deg) to periapsis (0 deg), and positive from periapsis to apoapsis. The objects located toward the center of the diagram correspond to events close to periapsis.

II. Navigation Strategy

Cassini's trajectory takes advantage of the substantial gravity assists provided by each Titan encounter. For example, a Titan flyby at an altitude of 1,000 km and 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 the spacecraft engine are dwarfed in comparison: about 98% of the total Δv required by the entire mission is provided by Titan alone.

If the majority of the Δv is provided by encounters with Titan, it follows that encounter inaccuracies are detrimental to the trajectory: missing a single Titan flyby would imply the end of the mission as planned. This observation is central to understanding the purpose of the Navigation team: execute propulsive maneuvers to attain accurate encounters.

The nominal navigation strategy consists of scheduling three maneuvers between each targeted encounter: a *cleanup* maneuver, about three days after an encounter, is used to remove the orbital dispersion errors incurred by inaccuracies in the flyby conditions; a *shaping* maneuver, normally located near apoapsis, is used to target the encounter conditions; an *approach* maneuver, about three days before an encounter, is used to refine the orbit before an encounter.

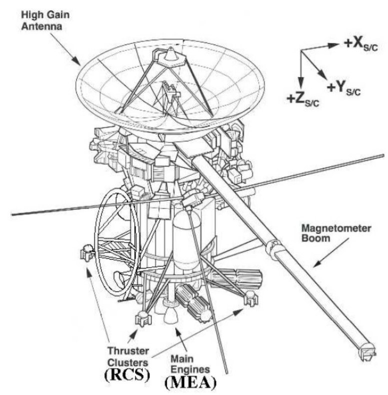

Figure 3. Cassini Orbiter

Maneuvers are performed by the Cassini's bipropellant Main Engine Assembly (MEA) or monopropellant Reaction Control Subsystem (RCS), (cf. Figure 3). The RCS consists of four hydrazine thruster clusters grouped into two sets: the first one is along $\pm\mathbf{Y}_{S/C}$, and is used to make balanced roll turns about the $\mathbf{Z}_{S/C}$ axis; the second one 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 ($\Delta v < 0.3$ m/s). MEA is used for larger maneuvers ($\Delta v \geq 0.3$ m/s).

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 imparted by the RCS do not impart $\Delta v$to the spacecraft. On the other hand, yaw turns executed by the RCS do impart 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. On the other hand, 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.

Maneuver execution errors are modeled via the methodology proposed by Gates,[15] which enables Δv statistical analysis and the determination of the maneuver delivery accuracy.[16,13] The underlying execution error parameters have been updated based on maneuver performance during the Saturnian tour.[17,18]

Typically the first two maneuvers are deterministic: their execution is required, regardless of uncertainty or errors, 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.[11] On the other hand, the approach maneuver is typically statistical: its execution depends on the accumulation of random error. The maneuvers are targeted to the upcoming encounter's three **B**-plane[12,13] flyby conditions: the spatial components $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$, and the time of flight. These targets have been determined during the mission design phase, and are collectively known as the *reference trajectory*.

A planned maneuver can be canceled 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; a common cancellation case is an approach maneuver preceded by accurate shaping maneuvers. These criteria are subordinate to science requirements. A more detailed account of the Project's maneuver cancellation process is provided in.[14]

Depending on science requirements, certain encounters admit the modification of targeting parameters. Such modification can be necessary for two reasons: (1) when a maneuver is smaller than the smallest implementable maneuver (about 0.009 mm/s), it is possible to modify the encounter time by a few tenths-of-second and artificially increase the maneuver magnitude,[9] and (2) some target modifications to the spatial components $\mathbf{B}\cdot\mathbf{R}$ and$\mathbf{B}\cdot\mathbf{T}$ can yield downstream Δv savings (about 1 gram of hydrazine per mm/s saved).

III. Targeted Encounters

Table 1 lists the targeted encounter conditions, and the reconstructed flyby differences for each of the 14 flybys from T78 to T84, three of which had their flyby parameters modified: two in the **B**-plane coordinates, and one in the time of closest approach.

Table 1. Targeted Encounter History (Titan-78 to Titan-84)

Encounter	Flyby Characteristics			Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0)				Flyby Differences from Reference Trajectory		
	V_∞	Period	Inc.	**B** · **R**	**B** · **T**	t_{CA}	Alt.	Δ**B** · **R**	Δ**B** · **T**	Δt_{CA}
	km/s	days	deg	km	km	ET SCET	km[*]	km	km	sec
Titan-78[†]	5.61	17.7	0.3	−2948.62	8160.97	12-Sep-2011 02:51:12	5821	1.34	0.44	−0.05
Enceladus-14	7.43	17.8	0.2	306.59	163.44	01-Oct-2011 13:53:32	100	−0.74	1.16	−0.10
Enceladus-15[†]	7.48	17.8	0.2	−365.69	1437.71	19-Oct-2011 09:23:18	1236	0.18	−0.39	−0.04
Enceladus-16[†]	7.38	17.9	0.2	629.00	−403.75	06-Nov-2011 04:59:59	500	0.57	−0.69	0.15
Dione-3[§]	8.70	17.5	0.2	256.76	−608.78	12-Dec-2011 09:40:29	100	0.77	−1.75	0.64
Titan-79	5.49	23.5	0.9	−3654.83	5316.20	13-Dec-2011 20:12:30	3586	−6.11	−7.63	−0.81
Titan-80[‡]	5.44	24.2	1.6	32167.96	−2828.99	02-Jan-2012 15:14:44	29415	94.24 *(+93.9)*	−51.63 *(−51.5)*	0.08
Titan-81	5.39	23.5	1.4	33951.59	−2051.12	30-Jan-2012 13:40:54	31131	−0.43	2.19	0.08
Titan-82	5.55	17.9	0.4	−3758.26	5502.71	19-Feb-2012 08:44:23	3803	0.88	0.26	−0.03
Enceladus-17[‡]	7.48	17.8	0.4	279.90	160.06	27-Mar-2012 18:31:15	75	−0.44	1.14	0.20 *(+0.3)*
Enceladus-18[‡]	7.48	17.8	0.4	295.18	129.72	14-Apr-2012 14:02:44	75	−1.60 *(−1.8)*	3.83 *(3.5)*	−0.008
Enceladus-19	7.51	17.8	0.4	318.82	48.13	02-May-2012 09:32:35	75	−0.46	−0.20	−0.008
Titan-83	5.43	16.0	15.8	−2894.99	−2495.50	22-May-2012 01:11:17	955	**TBD**	**TBD**	**TBD**
Titan-84	5.45	23.9	21.1	−3496.63	1548.74	07-Jun-2012 00:08:27	959	**TBD**	**TBD**	**TBD**

[*] Flyby altitude was not explicitly targeted in maneuver designs; reported altitude is relative to a sphere and is the reference trajectory value.

[†] Flyby differences from reference trajectory target conditions may appear large due to cancelled maneuvers.

[‡] Target parameters purposefully modified; the quantity in parentheses denotes the difference from the reference trajectory.

[§] Part of the Dione-3/Titan-79 double flyby, where Titan-79 was the targeted encounter.

IV. Maneuver History from June 2011 to June 2012

The maneuver design and reconstruction history from June 24, 2011 through June 10, 2012, covering OTM-287 to OTM-326, is presented in Table 2, where maneuvers are grouped by the corresponding targeted encounters. The table lists the maneuver epoch; true anomaly; central angle; design and reconstructed Δv; and engine type (MEA or RCS). The reported true anomaly corresponds to the instantaneous Saturn-centered orbit at burn time; central angle corresponds to the three-dimensional angle between the position vectors at the burn time and encounter (counting multiple revolutions). The encounter rows contain the encounter name, the time of closest approach, the flyby altitude, Δv imparted to the spacecraft from the encounter, whether the flyby is inbound or outbound[a], the days to the next encounter, and, if the target was

[a] An outbound flyby occurs after pericrone (Saturn periapsis). An inbound encounter occurs before pericrone.

modified, the change in the aimpoint or time of flight.

Encounter T77 and OTM-277 were discussed in previous work,[10] but are included in Table 2 to provide context for OTM-288 and the following maneuvers targeting T78. Out of 38 scheduled maneuvers, 9 were performed with MEA, 14 with RCS, and 15 were canceled; OTM-310 and OTM-322 were performed in their backup window (as indicated by the *BU* suffix in their name).

Table 3 lists the Δv characteristics of each maneuver covered in the scope of this paper, including the maneuver location (true anomaly and central angle), the Δv magnitude, and the roll and yaw turn angles to orient the maneuver burns. Each maneuver has two designs, one at the prime window and one at the backup window. Backup maneuver windows are usually scheduled 24 hours after the prime maneuver windows. Data from the maneuver designs that were implemented on the spacecraft for execution are shaded in gray.

Encounter **T78** $r_{CA} = 5821$ km — *12-Sep-2011 02:51:12 ET*

OTM-288 was used to provide an slight deterministic component (about 0.022 m/s) and correct the remaining aimpoint error in the T78 **B**-planeleft by the previous flyby (T77) and cleanup maneuver (OTM-287).

The team considered executing OTM-288 maneuver during its backup window—an alternative which could have provided savings of about 0.050 m/s. On the other hand, a failed backup would have incurred a penalty of about 0.3 m/s. A decision was made to select the prime window, foregoing Δv savings in favor of a viable and economical backup window.

OTM-288a was an auxiliary maneuver slot. It was allocated should the size of OTM-289 become too large for the RCS, as it is undesirable to execute an approach maneuver with the MEA. Neither this auxiliary maneuver nor the approach maneuver OTM-289 turned out to be necessary: the accuracy in the T77 flyby conditions and execution of OTM-288 were sufficient to attain the desired T78 flyby conditions.

The T78 flyby dropped the orbital period of Cassini to about 17.8 days, entering into a 13:1 resonance with Enceladus (cf. Table 1), thus enabling the upcoming three encounters.

Encounter **E14** $r_{CA} = 100$ km — *01-Oct-2011 13:53:32 ET*

No cleanup maneuver was required after the T78 flyby: the small deterministic component of OTM-290 (0.004 m/s) and T78 dispersion error (about 0.011 m/s) were optimally absorbed by OTM-291.

The shaping maneuver OTM-291 was used to rotate the line of nodes, thus enabling three back-to-back Enceladus flybys. As such, this maneuver was required to remain in the tour, and its deterministic component relatively large.

The approach maneuver OTM-292 was required to correct errors in the order of 10 km in position and 2 sec in time of closest approach to Enceladus; in addition to the impact to scientific observations, leaving this errors uncorrected would have led to a downstream penalty of about 1 m/s.

While the gravity field of Enceladus is small, the low altitude of this flyby did impart a 6 m/s gravitational assist to the spacecraft.

Encounter **E15** $r_{CA} = 1,236$ km — *19-Oct-2011 09:23:18 ET*

The reference trajectory relied on a single deterministic maneuver to attain the E15 target: OTM-294. Despite its relatively low deterministic Δv (0.016 m/s), this maneuver was responsible for correcting the flyby conditions by more than 500 km in position and almost 1 hour and 14 minutes in time of closest approach to Enceladus.

The original implementation of OTM-294 required a yaw turn of almost 84 degrees, which strained the RWA. To reduce the required turn on RWA, RCS turns were placed before and after the maneuver location (an operational technique known as *maneuver bracketing*). This technique did remove the concerns with RWA turns, but doubled the size of the maneuver from 0.036 to 0.075 m/s.

As an alternative to the bracketing technique, the Navigation Team considered canceling OTM-294, and wait until OTM-295 (an otherwise statistical maneuver) to implement the burn. However, this strategy was found to incur a downstream penalty of about 0.19 m/s. Furthermore, it did not guarantee that OTM-295 itself would not run into RWA problems; the alternative was later rejected. The approach maneuver OTM-295 was not required

Table 2. Maneuver History (OTMs 287–326)

Maneuver	Orbit Location	Maneuver Time (UTC SCET)	True Anomaly (deg)	Central Angle (deg)	Total* Design Δv Mag. (m/s)	Total* Design Δv RA (deg)	Total* Design Δv DEC (deg)	Total* Reconstructed Δv Mag. (m/s)	Total* Reconstructed Δv RA (deg)	Total* Reconstructed Δv DEC (deg)	Burn Type
Titan-77 (T77): 20-Jun-2011 18:33:06.6 ET SCET, Alt. = 1359 km, Flyby Δv= 773.2 m/s, Outbound, 83.3 days to T78, ΔTF= −0.4 sec											
OTM-287	T77+3d	24-Jun-2011 08:42	163.23	1137.86	0.146	206.06	3.20	0.145	205.51	3.52	RCS
OTM-288	∼peri	22-Aug-2011 15:04	−100.27	321.06	0.093	340.69	−3.38	0.092	340.44	−3.08	RCS
OTM-288a	∼apo	01-Sep-2011 22:03	176.90	43.58	.... *CANCELLED*						
OTM-289	T78−3d	09-Sep-2011 03:48	−160.85	21.34	.... *CANCELLED*						
Titan-78 (T78): 12-Sep-2011 02:51:12 ET SCET, Alt. = 5821 km, Flyby Δv= 386.9 m/s, Inbound, 19.5 days to E14											
OTM-290	T78+3d	15-Sep-2011 13:47	143.22	164.54	.... *CANCELLED*						
OTM-291	∼apo	20-Sep-2011 03:17	171.26	136.51	5.054	193.19	−70.89	5.054	193.33	−70.89	MEA
OTM-292	E14−3d	28-Sep-2011 13:02	−157.49	105.27	0.033	104.53	−1.76	0.033	104.76	−1.91	RCS
Enceladus-14 (E14): 01-Oct-2011 13:53:32 ET SCET, Alt. = 100 km, Flyby Δv= 5.6 m/s, Inbound, 17.8 days to E15											
OTM-294	E14+4d	05-Oct-2011 02:17	158.83	149.00	0.075	66.18	−15.05	0.075	66.24	−15.39	RCS
OTM-295	∼apo	10-Oct-2011 02:01	178.37	129.45	.... *CANCELLED*						
Enceladus-15 (E15): 19-Oct-2011 09:23:18 ET SCET, Alt. = 1236 km, Flyby Δv= 1.3 m/s, Inbound, 17.8 days to E16											
OTM-296	E15+3d	21-Oct-2011 01:31	142.01	166.30	.... *CANCELLED*						
OTM-297	∼apo	28-Oct-2011 11:17	−179.86	128.14	0.046	58.44	−13.21	0.046	58.49	−13.57	RCS
OTM-298	E16−3d	03-Nov-2011 00:47	−158.24	106.52	.... *CANCELLED*						
Enceladus-16 (E16): 06-Nov-2011 04:59:59 ET SCET, Alt. = 500 km, Flyby Δv= 2.6 m/s, Inbound, 36.2 days to D3											
OTM-299	E16+3d	09-Nov-2011 00:17	153.99	711.47	2.088	91.97	−55.72	2.086	91.42	−55.62	MEA
OTM-300	∼peri	24-Nov-2011 05:18	15.07	490.43	2.975	344.82	5.88	2.976	345.07	5.79	MEA
OTM-300c	∼peri	24-Nov-2011 21:33	121.27	383.99	.... *CONTINGENCY*						
OTM-300a	∼apo	01-Dec-2011 23:04	176.36	328.87	0.021	251.21	6.64	0.022	251.10	6.66	RCS
OTM-301	T79−4d	09-Dec-2011 08:49	−154.31	299.55	0.018	129.67	−67.39	0.019	130.08	−67.45	RCS
Dione-3 (D3): 12-Dec-2011 09:40:29 ET SCET, Alt. = 100 km, Flyby Δv= **TBD** *m/s, Outbound, 1.4 days to T79*											
Titan-79 (T79): 13-Dec-2011 20:12:30 ET SCET, Alt. = 3586 km, Flyby Δv= 506.0 m/s, Outbound, 19.8 days to T80											
OTM-303	T79+4d	17-Dec-2011 08:20	161.08	61.02	0.513	260.73	48.13	0.507	261.18	48.27	MEA
OTM-304	∼apo	22-Dec-2011 21:51	177.77	44.34	0.016	245.46	13.42	0.017	245.36	13.41	RCS
Titan-80 (T80): 02-Jan-2012 15:14:44 ET SCET, Alt. = 29415 km, Flyby Δv= 101.9 m/s, In., 27.9 days to T81, $\Delta\mathbf{B}$= [+93.9, +51.5] km											
OTM-306	∼apo	16-Jan-2012 06:39	179.07	316.41	0.049	155.30	59.19	0.050	155.49	58.82	RCS
Titan-81 (T81): 30-Jan-2012 13:40:54 ET SCET, Alt. = 31131 km, Flyby Δv= 98.0 m/s, Outbound, 19.8 days to T82											
OTM-308	T81+4d	03-Feb-2012 05:27	161.72	60.68	0.136	214.57	28.36	0.136	214.08	28.20	RCS
OTM-309	∼apo	10-Feb-2012 12:28	−177.48	39.90	.... *CANCELLED*						
OTM-310	T82−3d	16-Feb-2012 04:43	−160.09	22.53	.... *DELAYED*						
OTM-310 BU	T82−2d	17-Feb-2012 04:29	−155.38	17.83	0.020	270.54	8.21	0.020	270.29	8.23	RCS
Titan-82 (T82): 19-Feb-2012 08:44:23 ET SCET, Alt. = 3803 km, Flyby Δv= 485.3 m/s, Inbound, 37.4 days to E17											
OTM-311	T82+4d	23-Feb-2012 04:14	147.44	520.39	.... *CANCELLED*						
OTM-312	∼per	10-Mar-2012 03:01	15.73	292.01	3.575	181.06	16.20	3.566	181.00	16.15	MEA
OTM-312a	∼apo	16-Mar-2012 02:46	170.61	137.04	0.105	249.84	3.92	0.104	249.40	4.11	RCS
OTM-313	E17−3d	24-Mar-2012 16:02	−157.82	105.51	0.016	259.92	4.89	0.017	259.80	4.91	RCS
Enceladus-17 (E17): 27-Mar-2012 18:31:15.3 ET SCET, Alt. = 75 km, Flyby Δv= 6.0 m/s, Inbound, 17.8 days to E18, ΔTF= +0.3 sec											
OTM-314	E17+4d	31-Mar-2012 01:32	157.43	150.24	0.145	30.47	54.37	0.143	31.20	54.55	RCS
OTM-315	∼apo	05-Apr-2012 08:47	178.64	129.03	.... *CANCELLED*						
OTM-316	E18−3d	11-Apr-2012 14:48	−156.95	104.63	0.031	257.19	5.37	0.032	257.00	5.41	RCS
Enceladus-18 (E18): 14-Apr-2012 14:02:44 ET SCET, Alt. = 75 km, Flyby Δv= **TBD** *m/s, In, 17.8 days to E19, $\Delta\mathbf{B}$= [−1.8, +3.5] km*											
OTM-317	E18+3d	18-Apr-2012 00:18	158.26	149.07	.... *CANCELLED*						
OTM-318	∼apo	24-Apr-2012 07:33	−177.82	125.19	0.246	335.71	39.01	0.240	337.17	39.29	MEA
OTM-319	E19−3d	29-Apr-2012 07:17	−157.81	105.15	0.035	283.57	5.46	0.035	283.37	5.55	RCS
Enceladus-19 (E19): 02-May-2012 09:32:35 ET SCET, Alt. = 75 km, Flyby Δv= **TBD** *m/s, Inbound, 19.7 days to T83*											
OTM-320	E19+4d	06-May-2012 06:47	160.98	344.74	.... *CANCELLED*						
OTM-321	∼apo	14-May-2012 06:01	−170.70	316.45	8.272	333.25	−83.07	8.267	333.62	−83.03	MEA
OTM-322	T83−3d	19-May-2012 05:46	−132.21	277.94	.... *DELAYED*						
OTM-322 BU	T83−2d	19-May-2012 22:16	−95.59	241.33	0.082	201.41	−20.95	**TBD**	**TBD**	**TBD**	RCS
Titan-83 (T83): 22-May-2012 01:11:17 ET SCET, Alt. = 955 km, Flyby Δv= **TBD** *m/s, Outbound, 16.0 days to T84*											
OTM-323	T83+3d	25-May-2012 05:16	168.71	338.95	.... *CANCELLED*						
OTM-324	∼apo	30-May-2012 05:00	−172.82	320.48	3.714	260.35	−73.17	**TBD**	**TBD**	**TBD**	MEA
OTM-325	T84−3d	03-Jun-2012 21:15	−140.22	287.89	0.038	155.62	−9.19	**TBD**	**TBD**	**TBD**	RCS
Titan-84 (T84): 07-Jun-2012 00:08:2 ET SCET, Alt. = 959 km, Flyby Δv= **TBD** *m/s, Outbound, 47.8 days to T85*											
OTM-326	T84+3d	10-Jun-2012 10:29	158.82	693.46	0.422	271.83	16.50	**TBD**	**TBD**	**TBD**	MEA

* The total aggregates the Δv due to the burn, roll, and yaw turns; the pointing-bias-fix turn for MEA burns; and the deadband tightening for RCS burns; RA/DEC are measured with respect to the Earth mean equator and equinox of J2000.

Table 3. Maneuver Window Characteristics (OTMs 287–326)

OTM	Prime Maneuver Window					Backup Maneuver Window				
	True Anom. (deg)	Central Angle (deg)	Δv Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	True Anom. (deg)	Central Angle (deg)	Δv Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)
287	163.23	1137.86	0.1456	114.37	−163.64	166.93	1134.15	0.1809	112.69	−159.11
288	−100.27	321.06	0.0925	75.80	−33.81	95.95	124.63	0.0433	72.97	−28.06
288a	176.90	43.58	0.0152	−99.80	−46.52	179.59	40.90	0.0160	−99.45	−47.81
289	−160.85	21.34	0.0154	88.09	−113.61	−155.91	16.40	0.0238	88.43	−110.49
290	143.22	164.54	0.0150	−110.77	−104.10	153.58	154.19	0.0153	−128.06	−105.12
291	171.26	136.51	5.0542	101.38	−111.19	174.65	133.13	4.6052	102.35	−112.78
292	−157.49	105.27	0.0330	8.95	−87.14	−149.59	97.39	0.0606	9.01	−88.23
294	158.83	149.00	0.0746	103.97	−51.62	164.03	143.79	0.0913	100.00	−51.13
295	178.37	129.45	0.0155	−131.91	−18.00	−178.53	126.34	0.0158	−140.46	−15.70
296	142.01	166.30	0.0150	159.03	−26.66	152.85	155.44	0.0151	171.42	−34.70
297	−179.86	128.14	0.0459	32.84	−42.11	−176.73	125.02	0.0559	28.28	−45.28
298	−158.24	106.52	0.0173	−93.49	−164.88	−150.80	99.07	0.0183	−107.99	−163.49
299	153.99	711.47	2.0879	151.01	−81.97	160.43	705.02	2.2419	148.63	−73.79
300*	15.07	490.43	2.9755	96.35	−35.89	121.27	383.99	6.5586	46.30	−10.45
300a	176.36	328.87	0.0207	−159.01	−131.30	179.43	325.80	0.0245	−160.92	−127.16
301	−154.31	299.55	0.0177	161.12	−102.90	−144.46	289.72	0.0857	174.53	−105.27
303	161.08	61.02	0.5127	−114.43	−103.72	164.82	57.28	0.5607	−118.73	−108.52
304	177.77	44.34	0.0164	−146.30	−135.43	−179.73	41.84	0.0192	−148.70	−133.89
306	179.07	316.41	0.0492	12.48	−100.25	−178.51	314.00	0.0474	14.80	−98.74
308	161.72	60.68	0.1359	−96.27	−142.27	165.38	57.04	0.1485	−105.18	−143.33
309	−177.48	39.90	0.0150	177.31	−56.12	−174.92	37.34	0.0165	178.16	−58.74
310	−160.09	22.53	0.0160	168.03	−106.93	−155.38	17.83	0.0197	−163.48	−115.48
311	147.44	520.39	0.0457	−6.13	−47.33	156.02	511.81	0.0427	5.04	−45.40
312	15.73	292.01	3.5749	−126.01	−141.78	132.06	175.61	10.2007	133.54	−166.98
312a	170.61	137.04	0.1047	−78.70	−135.63	174.01	133.64	0.1242	−80.20	−131.80
313	−157.82	105.51	0.0163	−71.08	−125.23	−150.26	97.94	0.0207	−82.06	−91.31
314	157.43	150.24	0.1445	−4.65	−46.59	162.95	144.71	0.1201	7.06	−39.23
315	178.64	129.0	0.0152	131.89	−20.17	−178.25	125.92	0.0153	128.39	−19.23
316	−156.95	104.63	0.0314	−69.88	−126.69	−148.93	96.60	0.0485	−73.63	−116.38
317	158.26	149.07	0.0062	−99.17	−82.01	163.60	143.73	0.0079	−93.20	−71.87
318	−177.82	125.19	0.2458	−38.59	−51.90	−174.64	122.01	0.2658	−50.64	−56.94
319	−157.81	105.15	0.0350	−77.12	−99.70	−150.23	97.58	0.0610	−79.61	−92.44
320	160.98	344.74	0.0232	−135.39	−99.40	165.72	340.02	0.0428	−145.54	−96.06
321	−170.70	316.45	8.2722	8.38	−89.61	−166.88	312.62	8.2920	10.01	−89.68
322	−132.21	277.94	0.0407	−79.64	−153.71	−95.59	241.33	0.0822	−7.55	−165.63
323	168.71	338.95	0.0006	−147.97	−63.13	172.76	334.90	0.0007	−156.74	−75.53
324	−172.82	320.48	3.7142	−168.02	−102.57	−168.78	316.45	3.6320	−169.10	−102.32
325	−140.22	287.89	0.0375	−61.81	−133.80	−125.45	273.12	0.0509	−66.48	−148.05
326	158.82	693.46	0.4216	−168.31	−105.14	162.94	689.35	0.4910	−176.05	−89.41

* The backup window for OTM-300 was OTM-300c (contingency), which was scheduled 12 hours prior to the nominal OTM-300 BU time.

Encounter **E16** $r_{CA} = 500$ km *06-Nov-2011 04:59:59 ET*

OTM-296 was canceled because the optimal strategy for cleaning up after the E15 flyby allocated all the Δv into OTM-297, which remained a relatively small maneuver (0.046 m/s).

An interesting scenario took place in the E15 to E16 transfer: the cancellation of both OTM-296 and OTM-297 would have resulted in Δv savings of about 0.164 m/s. However, the propellant savings came at the cost of modifying the E16 encounter by 120 km in range and 12 minutes in time of closest approach. Considering that the scientific observations scheduled for E16 (RADAR) required altitude preservation, this otherwise interesting alternative—effectively an unplanned double flyby—was quickly discarded. No approach maneuver was required to attain E16.

Encounter **D3/T79** $r_{CA} = 100/3,586$ km *12-Dec-2011 09:40:29 ET / 13-Dec-2011 20:12:30 ET*

The reference trajectory allocated four maneuvers to target the last double flyby scheduled in the mission: OTM-299 and OTM-300, both with relatively large deterministic components (2.192 m/s and 2.949 m/s, respectively), followed by the purely statistical OTM-300a (auxiliary maneuver) and OTM-301; the auxiliary maneuver was placed to ensure that the magnitude of OTM-301 would remain within RCS bounds.

The shaping maneuver OTM-300—intended to raise apoapsis altitude by over 10,000 km—was located very close to Saturn periapsis (15° true anomaly). In contrast—and only 28 hours later—its backup window was located at a true anomaly of 135°. The effectiveness of a maneuver to increase apoapsis range decreases rapidly as the location moves away from periapsis. In fact, the backup window was located so far away from periapsis that the desired change in orbital elements could not be attained by a single maneuver. As a consequence, the penalty of executing OTM-300 in its backup window was a prohibitively expensive 8.6 m/s, even after allowing for a large miss in D3/T79.

Missing the prime maneuver window is a low-probability event; it has happened once during the lifetime of the spacecraft—OTM-123, in August 2007, due to a ground transmitter problem. To further reduce such probability, six command uplink opportunities were scheduled in advance. With a virtually guaranteed uplink, the remaining failure mode was spacecraft safing prior to maneuver execution (which has never happened).

After extensive analysis, the Navigation and Spacecraft Operations Teams determined that a contingency maneuver—OTM-300c—would be scheduled in the event of spacecraft safing. Such maneuver would be placed twelve hours after the prime pass (instead of the original 28 hours), and the original D3/T79 aimpoints would be given up in favor of aimpoints optimized for return the spacecraft to the reference trajectory. This contingency scenario would have lead to a 6 m/s cost (2.6 m/s less than the original backup), and missed scientific observations in D3 and T79. However, it would have enabled the spacecraft to continue the tour as planned. Ultimately, no contingency scenario took place; OTM-300 was executed during its prime window.

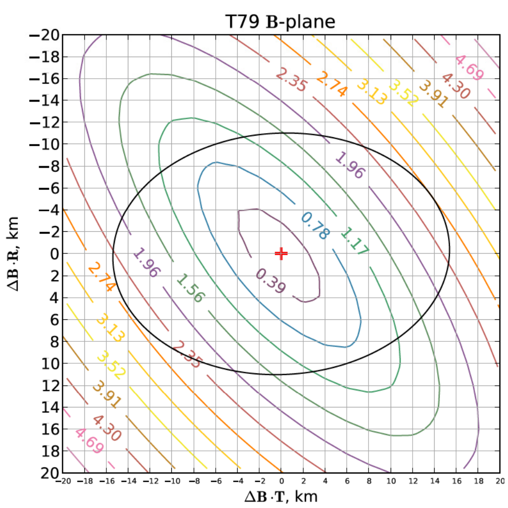

Figure 4. The delivery ellipse of OTM-301 mapped onto T79 shows the downstream Δv cost (in m/s) for a given miss on $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$.

In addition to the difficulty associated with producing a viable backup maneuver, the D3/T79 double flyby exhibited another complication. Determining what body to target in a double flyby is an added burden during maneuver design, and renders the supporting analytical work considerably more intricate. In this case, the central complication stemmed from the order of the double flyby: Dione first, then Titan. The uncertainty in Dione's ephemeris, its relatively large gravitational parameter, and the low flyby altitude meant that a miss at Titan was inevitable. As presented in Figure 4, the reference trajectory predicted delivery uncertainty at Titan anticipated downstream penalties of up to 2.7 m/s at the 1-1σ level; Figure 5 presents the difference in time of closest approach and altitude at Titan as a function of the **B**-plane miss at Dione. As the spacecraft

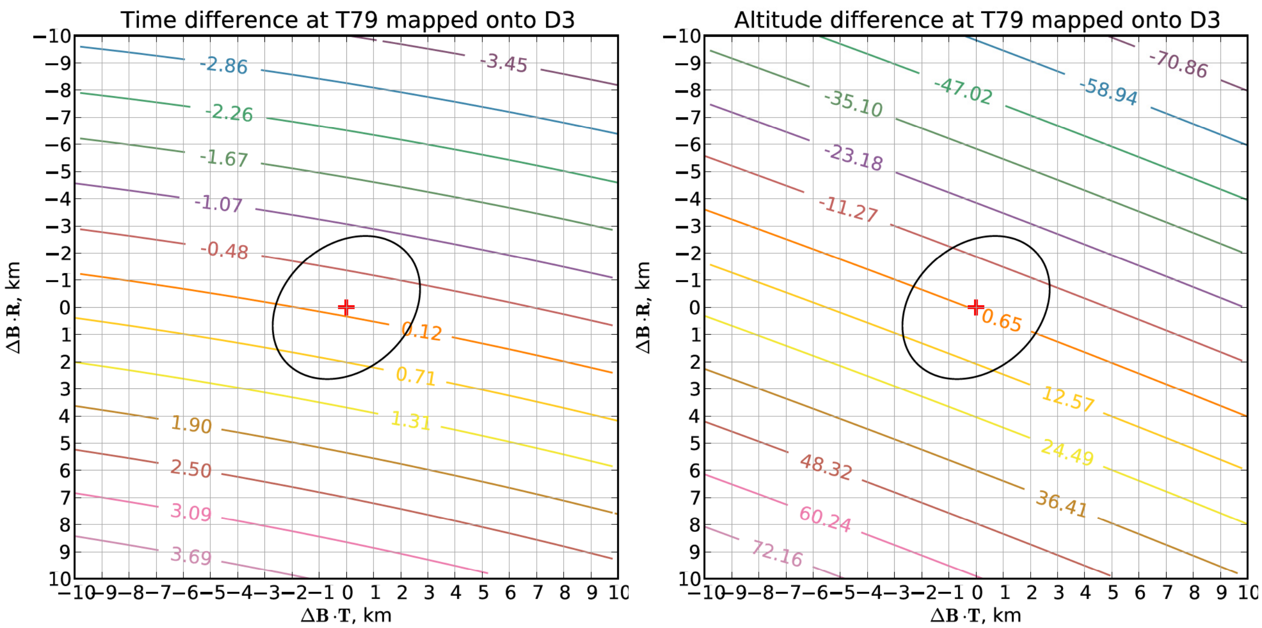

Figure 5. Difference in time of closest approach to Titan (in seconds; left) and flyby altitude (in km, right) as a function of the B-plane miss in Dione; the delivery ellipse corresponds to the reference trajectory.

approached the double flyby, the delivery error was significantly reduced, and it was determined that the best navigation strategy would be to target T79 (targeting D3 would have implied a downstream penalty of over 3 m/s). Ultimately, the double flyby was a success, and the dispersion Δv was about 1.2 m/s, about half of what had been allocated.

Encounter **T80** $r_{CA} = 29,415$ km *02-Jan-2012 15:14:44 ET*

After a successful double flyby, it was determined that a maneuver design targeting a different **B**-plane location on T80 would yield significant Δv savings (0.6 m/s). The shift was determined to be 93.9 km in $\mathbf{B} \cdot \mathbf{R}$ and -51.5 km in $\mathbf{B} \cdot \mathbf{T}$.

The target change resulted in an increase in altitude of about 98 km. However, in part due to the high flyby altitude, this altitude change was deemed acceptable from a scientific perspective, and it lead the overall trajectory to adjust asymptote errors incurred after the double flyby. Even after a significantly different target at T80, the overall trajectory was closer to the reference trajectory after T80: the change in aimpoint effectively made Titan correct the asymptote difference. The approach maneuver OTM-304 was executed to attain a small savings of 0.18 m/s.

At this point in the trajectory, the Navigation Team had expected to pay about 3 m/s of downstream Δv due to the previous double flyby. However, the accurate D3/T79 paired with the savings incurred by modifying the T80 target, led to an effective Δv penalty of about 0.7 m/s: about 75%.

Encounter **T81** $r_{CA} = 31,131$ km *30-Jan-2012 13:40:54 ET*

Only one deterministic maneuver was scheduled between T80 and T81: OTM-306. This maneuver could have been canceled for a penalty of about 65 mm/s. However, its execution would nearly guarantee that the upcoming OTM-308 would remain within RCS size.

Encounter **T82** $r_{CA} = 3,803$ km *19-Feb-2012 08:44:23 ET*

The transfer from T81 to T82 followed a traditional three-maneuver approach. The optimization during the design of the cleanup maneuver OTM-308, removed the shaping component from OTM-309, effectively canceling the second maneuver in the transfer.

The magnitude of the approach maneuver OTM-310 was too small to be implementable. However, its cancellation would have led to a penalty of 0.18 m/s. The Maneuver Team originally proposed a modification of 1.8 seconds to the time of closest approach to increase the maneuver size and make it implementable; this modification would have lead to an acceptable 10 km difference in altitude. However, the spacecraft operations team determined that the turns required to bring the spacecraft to the burn attitude would strain the RWA subsystem.

Instead of bracketing the maneuver in between RCS turns to mitigate the RWA strain, it was decided to execute this maneuver during its backup window, with an uplink during the prime antenna pass.

The Navigation Team seldom chooses to execute a maneuver during the backup window. However, in this case the decision lead to savings of about 0.1 m/s, no RWA problems, no modification in time of closest approach, and an overall reduction in the difference between the actual and reference trajectories.

Encounter **E17** $r_{CA} = 75$ km *27-Mar-2012 18:31:15 ET*

The cleanup maneuver OTM-311 was canceled, and its Δv component was absorbed by OTM-312 with a savings of 0.075 m/s.

OTM-312 was a relatively large 3.575 m/s maneuver which would reduce the orbital period by about 3 hours to achieve an orbit resonant with Enceladus (13:1). However, the placement of OTM-312 presented a challenge similar to OTM-300: its location was near periapsis, and the backup strategy demanded the creation of contingency scenarios.

The lessons learned from OTM-300 were invaluable during this contingency design. A plan similar to that for OTM-300 was adopted: placing a maneuver 12 hours after the prime window, and execute it should the prime maneuver fail to execute due to spacecraft safing. This contingency plan would have resulted in a 4.5 m/s penalty, in contrast to an 8 m/s penalty which would correspond to the naïve placement of a backup maneuver 24 hours after the prime window.

OTM-312a was an auxiliary maneuver scheduled to ensure that OTM-313 would remain within RCS size. Indeed, its execution was required (Δv=0.105 m/s).

OTM-313 was a small RCS maneuver, below the implementation threshold. However, its cancellation would have lead to a downstream penalty of 0.3 m/s. Instead, it was decided that a modification in the time of closest approach by 0.4 seconds would be granted to grow the maneuver to an implementable size.

Encounter **E18** $r_{CA} = 75$ km *14-Apr-2012 14:02:44 ET*

The transfer from E17 to E19 required a relatively small deterministic Δv. Whereas two deterministic maneuvers were scheduled, the optimal allocation placed all the Δv in the cleanup maneuver OTM-314. This strategy enabled the cancellation of the shaping maneuver OTM-315, which in turn eased the quick turnaround that would have been required between OTM-315 and OTM-316.

During the design of the approach maneuver OTM-316 it was determined that a modification in the targeting parameters of -1.8 in $\mathbf{B} \cdot \mathbf{R}$ and 3.5 km in $\mathbf{B} \cdot \mathbf{T}$would yield savings of 0.133 m/s, and ensure that OTM-317 would remain an RCS maneuver. This target modification was deemed acceptable from a scientific perspective.

Encounter **E19** $r_{CA} = 75$ km *02-May-2012 09:32:35 ET*

The optimal Δv allocation for the transfer from E18 to E19 resulted in the cancellation of OTM-317 and a relatively small OTM-318.

The magnitude of OTM-318 (0.25 m/s) would normally have implied that the maneuver would be implemented by the RCS. However, the Spacecraft Operations desired to test a part of the spacecraft electrical system, and requested that the maneuver be executed with the main engine. This maneuver became the smallest MEA maneuver executed to date (only 1.3 seconds in duration). This provided a valuable data point for the modeling of the maneuver execution error, and provided a new lower-bound to the magnitude implementable by the MEA.

The approach maneuver OTM-319 was required to refine the **B**-plane approach which would have resulted in a 0.5 m/s cost if left uncorrected. In addition, it enabled the combination of OTM-320 and OTM-321 into a single maneuver. This maneuver needed to be bracketed to reduce the strain in the RWA subsystem.

Encounter **T83** $r_{CA} = 955$ km	*22-May-2012 01:11:17 ET*

The execution of OTM-319 enabled the combination of OTM-320 and OTM-321. For this reason, the cleanup maneuver was canceled, in favor of OTM-321.

OTM-321 was a large (8.272 m/s) main engine maneuver which would accomplish two important goals: (1) remove the spacecraft from a trajectory colliding with Titan (as per design), and (2) set up the encounter with T83 which would mark the end of the equatorial phase.

The burn direction for the shaping maneuver OTM-321 was nearly parallel to the Earth direction, which delayed its reconstruction from telemetry data. For this reason, the Orbit Determination Team requested one more day of telemetry data. To grant this additional day of telemetry, it was decided to implement the approach maneuver OTM-322 in its backup window.

Encounter **T84** $r_{CA} = 959$ km	*07-Jun-2012 00:08:27 ET*

As per design, the T83 flyby placed the spacecraft on a trajectory which would collide with Titan at T84. During the design of the cleanup maneuver, the optimal solution transferred all the cleanup cost to the shaping maneuver OTM-324, effectively canceling OTM-323.

The shaping maneuver OTM-324 was a relatively large main engine maneuver required to remove the spacecraft from its trajectory colliding with Titan.

After executing OTM-324, an small correction in the **B**-plane—mostly the incoming asymptote direction—was still required. Leaving the direction unmodified would have incurred a downstream cost of 0.7. m/s. The orientation of the delivery ellipse for the approach maneuver OTM-325 implied that even small flyby errors would incur downstream cost of up to 0.5 m/s. Indeed, the cleanup maneuver for T84 did remove 0.5 m/s from this expected dispersion.

V. Navigation Performance

Table 4 shows the maneuver performance per flyby, by comparing the reconstructed Δv from each encounter span to the planned Δv from the reference trajectory (see shaded columns). This maneuver performance is represented by the navigation Δv cost per encounter in the last column. The predicted Δv statistics per encounter span were garnered from statistical analyses reported in References 13 and 16, and later updated from covariance studies during operations.

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, a fact that can be seen in the large standard deviation of nearly 1 m/s for the Equinox Mission reported in the table. With the majority of the maneuvers performed on RCS during the Solstice Mission, the average navigation cost so far in the Solstice Mission has been less than half the average cost seen in the prior missions. However, the average navigation cost in the Solstice Mission is likely to increase because of more complex geometries and shorter turn-around times expected to design maneuvers. In addition, the current cost only takes into account one-fifth of the entire Solstice Mission. This was a period marked by long orbital transfers which provided more accurate OD data for the maneuver designs.

VI. Conclusions

The Cassini Navigation Team maintained the prescribed Saturn tour from June 2011 through June 2012 via the execution of 23 maneuvers, which successfully targeted 7 Titan flybys and 7 icy satellite encounters (six of Enceladus and one of Dione).

Table 4. Maneuver Performance per Encounter

Encounter Span	Ref. Traj. Det. Δv m/s	Predicted Δv Statistics Mean m/s	σ m/s	90%* m/s	Design Δv m/s	Recon. Δv m/s	Navigation Δv Cost† m/s
T77–T78	0.017	1.093	0.664	2.020	0.238	0.237	**0.220**
T78–E14	4.977	4.994	0.097	5.116	5.087	5.087	**0.110**
E14–E15	0.013	0.149	0.103	0.293	0.075	0.075	**0.061**
E15–E16	0.017	0.034	0.010	0.047	0.046	0.046	**0.030**
E16–D3/T79	5.140	5.411	0.216	5.694	5.102	5.103	**−0.037**
T79–T80	0.032	1.776	1.279	3.538	0.529	0.524	**0.492**
T80–T81	0.006	0.118	0.066	0.204	0.049	0.050	**0.045**
T81–T82	0.017	0.139	0.067	0.225	0.156	0.157	**0.140**
T82–E17	3.526	3.814	0.256	4.175	3.696	3.686	**0.160**
E17–E18	0.125	0.214	0.104	0.357	0.176	0.175	**0.049**
E18–E19	0.391	0.420	0.110	0.571	0.281	0.275	**−0.116**
E19–T83	8.266	8.382	0.100	8.515	8.354	**TBD**	*0.088*
T83–T84	3.720	3.922	0.177	4.164	3.752	**TBD**	*0.031*

* 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; figures shown are based on source data to avoid round-off errors.

Table 5. Average Navigation Δv Cost per Encounter

Mission	Flyby Span	Number of Flybys	Nav. Cost per Flyby Mean m/s	σ m/s
Prime (7/2004 – 9/2008)	Ta–E4	54	0.324	0.594
Equinox (9/2008 – 9/2010)	E5–T72	36	0.447	0.978
Solstice (9/2010 – 6/2012, First 2 Years)	T73–T84	22	0.109	0.132

The central challenges during the second year of operations were the fast orbits which lead to a period of constant turnaround of maneuver designs, the placement of maneuver near periapsis, which demanded the development of detailed contingency scenarios, and the double flyby D3/T79.

VII. Acknowledgments

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