Cassini Maneuver Experience: Ending the Equinox Mission

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The Cassini-Huygens spacecraft was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year interplanetary cruise, it entered a Saturnian orbit for a four-year Prime Mission in 2004 and began a two-year Equinox Mission in 2008. It has been approved for another seven-year mission, the Solstice Mission, starting in October 2010. This paper highlights significant maneuver activities performed from July 2009 to June 2010. We present results for the 45 maneuvers during this time. The successful navigation of the Cassini orbiter can be attributed in part to the accurate maneuver performance, which has greatly exceeded pre-launch expectations.

I. Overview

The Cassini-Huygens spacecraft (Fig. 1) was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year cruise, Cassini-Huygens entered orbit around Saturn for a four-year tour in July 2004. One of the mission's first activities was to release the Huygens probe to Titan, Saturn's largest moon, in January 2005. Since then the Cassini orbiter has been traveling in a series of highly elliptical orbits about Saturn, which is referred to as the "satellite tour." The mission is continuing the goal of studying Saturn's atmosphere, magnetosphere, rings, and satellites, including Titan's atmosphere and topography.

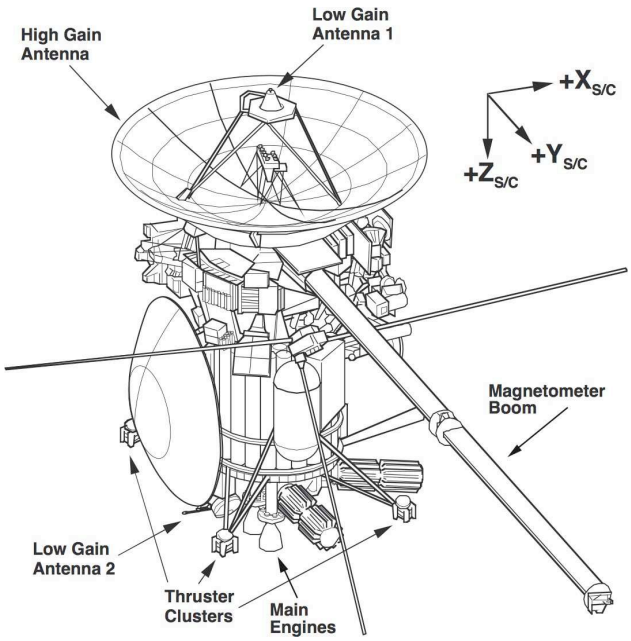

Figure 1: Cassini-Huygens Spacecraft. The Huygens probe (pictured on the left) was released in the first year[5] of the tour.

Earlier papers from the Cassini Navigation Team reported on a prelaunch analysis,[1] maneuvers planned and performed during early interplanetary cruise,[2] inner cruise,[3] end of cruise and arrival at Saturn,[4] the four-year Prime Mission,[5–8] and the first year of the Equinox Mission.[9]

Completing its second year of the Equinox Mission, the Cassini orbiter continues to obtain valuable data on Saturn, Titan, and Saturn's other satellites, thanks to a healthy spacecraft and successful navigation. The last year of the Equinox Mission has included six icy satellite flybys, two ansa-to-ansa (end-to-end) ring occultations, observations of the rings during Saturn's equinox, and a number of low-altitude Titan flybys. There were also two Enceladus plume occultations in the last year of the Equinox Mission.

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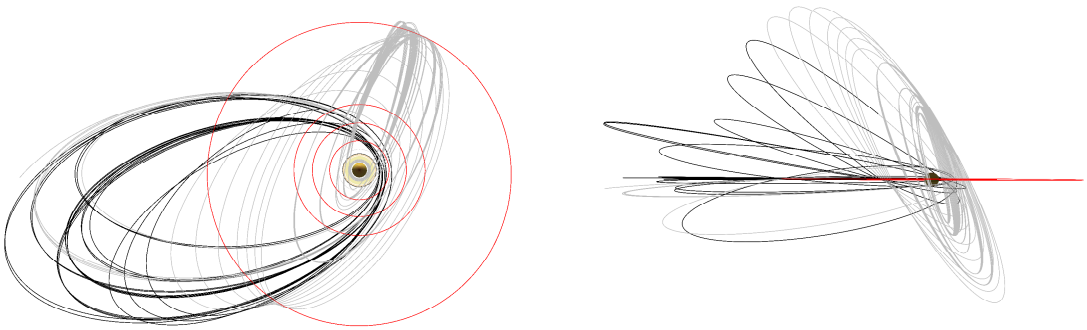
The four-year Prime Mission (July 2004–June 2008) included 161 Orbit Trim Maneuvers (OTMs), 52 encounters of Titan and other satellites, and 75 revolutions of Saturn. The two-year Equinox Mission (July 2008–September 2010) includes 104 OTMs, 38 targeted flybys of Titan and other icy satellites, and 60 revolutions of Saturn. From July 12, 2009 to June 5, 2010, there were 45 planned OTMs. These maneuvers, OTM-206 through OTM-250, were designed to target the Cassini orbiter to flyby aimpoints near Titan, Enceladus, Rhea, and Dione. Figure 2 shows the full Equinox Mission trajectory, with the last year of the trajectory in black. From October to December 2009 and from January to May 2010, the orbiter stayed close to Saturn's equatorial plane for many icy satellite flybys and two ansa-to-ansa occultations. The remainder of the time, the orbiter was slightly inclined with respect to Saturn's equatorial plane.



(a) Top View: Sun is towards the top (b) Equatorial View: Sun is into the page

Figure 2: Equinox Mission Trajectory: July 2008–July 2009 in gray, July 2009–June 2010 in black. The red circles are the orbits of Enceladus (smallest), Dione, Rhea, and Titan (largest).

The first four Titan encounters covered herein are Titan-59 (T59) to Titan-62 (T62), which had produced orbits decreasing in inclination, designed for viewing the rings during Saturn's equinox. Those encounters were targeted by OTMs 206–217. This sequence was followed by equatorial orbits with non-resonant transfers from T62–T68, targeted by OTMs 218–247. The last encounter leg, T68–T69, which includes OTMs 248–250, is concerned with Titan gravity measurements and an Enceladus plume occultation. OTMs 251–263 comprise the last maneuvers scheduled during the Equinox Mission through the end of September 2010; these maneuvers and the first year of the Solstice Mission will be discussed in detail in a future paper.

II. Maneuver Execution

Maneuvers are performed by the Cassini orbiter's bipropellant Main Engine Assembly (MEA) or monopropellant Reaction Control Subsystem (RCS). The MEA is used for large maneuvers, and the RCS is used for smaller maneuvers, attitude control, and reaction wheel desaturation (noted in Fig. 1). A component not shown in the diagram is the hemispherical clamshell-like cover for the main engine, which can be deployed to protect the engine nozzles from dust hazards.

The RCS consists of 4 hydrazine thruster clusters, a total of 8 primary and 8 backup thrusters. They are labeled in Figure 1. The thrusters are grouped into two sets. The first set faces the $\pm\, Y_{S/C}$ spacecraft directions; it is used to make balanced roll turns about the $Z_{S/C}$ axis. The other set faces the $-Z_{S/C}$ axis and is used to make unbalanced pitch turns about the $X_{S/C}$ axis yaw turns about the $Y_{S/C}$ axis.

Maneuvers are executed in a turn-and-burn style. The burn orientation is achieved by performing a roll turn followed by a yaw turn. The turns are reversed to return to the original attitude. If turns are performed with the RCS thrusters, then the yaw turns will impart ΔV, requiring that turn angles be computed so that the turn and burn ΔV sum properly. Turns performed with the Reaction Wheel Assembly (RWA) do not impart ΔV.

If a maneuver ΔV magnitude is greater than about 300 mm/s, MEA is utilized; otherwise, RCS is used. Gates models[10] of the maneuver execution errors for MEA and RCS are implemented for statistical analysis.[11,12] These models have been updated (Table 1) based on maneuver performance thus far in the Saturnian tour.[13]

The nominal navigation strategy employed since the beginning of the tour has been to schedule three

Table 1: Maneuver Execution-Error Model 2008-01 (1-σ)

		MEA	RCS
Magnitude	Proportional (%)	0.0	0.4
	Fixed (mm/s)	4.5	1.0
Pointing (per axis)	Proportional (mrad)	1.1	9.0
	Fixed (mm/s)	3.0	0.0

propulsive maneuvers between each targeted Titan or icy satellite encounter: a flyby cleanup maneuver and two targeting maneuvers (see Fig. 3). These are targeted to fixed encounter conditions defined by a reference trajectory. The cleanup maneuver is usually performed three days after an encounter, and is used to correct trajectory errors from a previous flyby. The first maneuver targeted to an encounter is typically performed near apocrone (Saturn apoapsis) to "shape" the trajectory in order to achieve the flyby conditions. The second targeting maneuver is generally executed three days before an encounter to clean up errors from the near-apocrone maneuver and to achieve as accurate flyby conditions as possible. The maneuvers are usually targeted to the upcoming encounter's three B-plane flyby conditions: the spatial components $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ and the time of flight (TF). For an explanation of the B-plane, see Ref. 14 and B-Plane Appendix in Ref. 1–9.

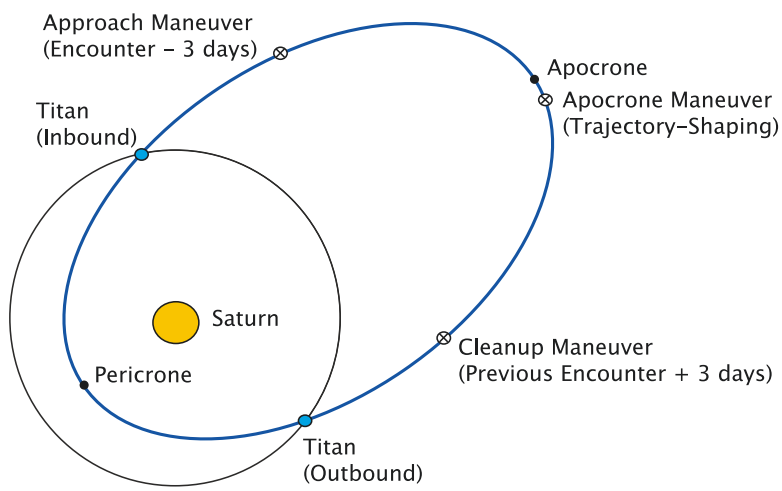


Figure 3: Maneuver Strategy for Saturn Tour. Shown here is an outbound-to-inbound leg. In between encounters are three maneuvers. The shaping maneuver is also known as the apocrone maneuver.

Flyby cleanup maneuvers are typically designed with a chained two-impulse optimization strategy, which minimizes the sum of the first two deterministic maneuvers in a leg (in this case, the cleanup and apocrone maneuvers) across several encounters. This minimizes propellant usage and helps control asymptote errors. The first maneuver in each encounter leg (the cleanup maneuver) is computed by minimizing the cost function

$$J_i = \underbrace{||\Delta\mathbf{V}_{i,1}|| + ||\Delta\mathbf{V}_{i,2}||}_{leg\ i} + \underbrace{||\Delta\mathbf{V}_{i+1,1}|| + ||\Delta\mathbf{V}_{i+1,2}||}_{leg\ i+1} + \cdots \tag{1}$$

$$= \sum_{m=0}^{n} \left(||\Delta\mathbf{V}_{i+m,1}|| + ||\Delta\mathbf{V}_{i+m,2}||\right) \tag{2}$$

subject to the constraints

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+1} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+1} = 0,\ \Delta\mathrm{TF}_{i+1} = 0,$$

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+2} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+2} = 0,\ \Delta\mathrm{TF}_{i+2} = 0,\quad \textit{etc. up to } (i+m). \tag{3}$$

It follows that for n downstream encounters beyond the current encounter, $2(n+1)$ maneuvers are being optimized ($6(n+1)$ parameters) and $3(n+1)$ constraints are imposed ($\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and TF). Besides providing an optimal distribution of the ΔVs over multiple legs, this optimization strategy helps control asymptote errors without actively altering downstream flyby aimpoints after each encounter. Controlling the asymptote errors are accomplished by floating the perturbed state location for the apocrone maneuver. Another benefit of this strategy is that the designed cleanup maneuver ΔVs are less sensitive to maneuver time shifts.[15]

As an exception, we can also target the cleanup maneuver to the Cartesian state of the apocrone maneuver. This strategy is called "XYZ targeting." In this strategy, the perturbed state location $\Delta\mathbf{r}$ for the apocrone maneuver is constrained, usually to the reference trajectory position of the apocrone maneuver. The XYZ targeting strategy is chosen when the ΔV cost is moderate enough to be justified and approved by the Cassini project for extra science objectives such as occultations and/or double flybys.

III. Summary of Navigation Performance

Table 2 lists the targeted encounter conditions and the achieved flyby differences for each encounter from T59 to T69. Of the 15 targeted encounters, 10 of them had cancelled maneuvers in their respective trajectory legs. The large target difference at T61 is attributed to the intentional targeting of a different aimpoint (see Section VII.B). The large miss for Enceladus-8 (E8) resulted from cancelling maneuvers and not targeting the nominal encounter conditions (see Section VII.C). The miss at Rhea-2 (R2) came from finding out after the flyby that the estimate for the position of Rhea was off by ∼3 km when the flyby was being targeted.[16] Error in the Dione-2 (D2) flyby was mainly due to a 3 km error in the Dione ephemeris. The large differences in both T67 and E10 arose because they were both non-targeted encounters in double flybys (see Section V).

Table 2: Targeted Encounter History (Titan-59 to Titan-69)

Encounter			Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0)				Flyby Differences from Reference Trajectory		
Inbound (I) *Outbound (O)*		V_∞ (km/s)	$\mathbf{B}\cdot\mathbf{R}$ (km)	$\mathbf{B}\cdot\mathbf{T}$ (km)	Time of Closest Approach (ET SCET)	Alt.* (km)	$\mathbf{B}\cdot\mathbf{R}$ (km)	$\mathbf{B}\cdot\mathbf{T}$ (km)	TCA (s)
Titan-59† (T59)	*I*	5.55	3682.34	981.64	24-Jul-2009 15:35:09	955	1.44	−1.17	0.14
Titan-60† (T60)	*I*	5.55	3613.32	1257.75	09-Aug-2009 14:04:59	970	1.07	−0.04	0.10
Titan-61† (T61)	*I*	5.54	2801.51	−2607.11	25-Aug-2009 12:52:44	970	2.04	16.10	−0.41
Titan-62 (T62)	*I*	5.56	2318.47	3448.40	12-Oct-2009 08:37:30	1300	0.52	−1.02	0.19
Enceladus-7 (E7)	*O*	7.74	308.30	160.15	02-Nov-2009 07:43:04	100	1.10	−2.36	−0.14
Enceladus-8† (E8)	*I*	7.75	1606.22	920.72	21-Nov-2009 02:10:56	1604	16.48	−42.67	6.62
Titan-63† (T63)	*O*	5.47	−2214.92	−7395.04	12-Dec-2009 01:04:20	4850	4.86	1.15	−0.27
Titan-64† (T64)	*O*	5.49	−3521.26	−1470.24	28-Dec-2009 00:18:05	955	3.51	1.20	−0.37
Titan-65 (T65)	*O*	5.50	3602.39	1579.09	12-Jan-2010 23:11:42	1073	1.92	−1.33	−0.09
Titan-66† (T66)	*O*	5.53	5914.63	8499.34	28-Jan-2010 22:29:55	7490	0.73	−5.30	0.69
Rhea-2† (R2)	*I*	8.55	−700.55	−509.28	02-Mar-2010 17:41:42	100	−3.12	3.36	−0.08
Titan-67‡ (T67)	*I*	5.51	4798.61	−9145.49	05-Apr-2010 15:51:44	7462	−21.09	16.61	15.78
Dione-2 (D2)	*I*	8.36	−468.37	952.08	07-Apr-2010 05:17:17	500	−0.62	6.98	0.01
Enceladus-9† (E9)	*O*	6.51	307.00	162.74	28-Apr-2010 00:11:23	100	1.10	0.98	0.03
Enceladus-10†,‡ (E10)	*I*	6.52	568.88	−383.93	18-May-2010 06:05:46	439	3.61	0.52	0.33
Titan-68† (T68)	*O*	5.48	3960.88	−1577.78	20-May-2010 03:25:26	1400	−2.40	0.36	0.28
Titan-69 (T69)	*O*	5.49	−4632.25	−1620.97	05-Jun-2010 02:27:33	2044	1.35	1.06	−4e-3

* Flyby altitude was not explicitly targeted in maneuver designs. Reported altitude is relative to a sphere.

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

‡ Non-targeted encounter in double flyby.

The complete maneuver design and reconstruction history from OTM-206 to OTM-250 is presented in Table 3. This table shows the maneuvers separated by the encounters, in chronological order. The information includes the maneuver epoch; the true anomaly; the central angle; the design total ΔV magnitude, right ascension, and declination; the reconstructed ΔV; and the engine type (MEA or RCS). The true anomaly listed is for an osculating ellipse with respect to Saturn, and it indicates where the spacecraft was in the orbit

Table 3: Maneuver History (OTMs 206–250)

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-58 (T58): 08-Jul-2009 17:05:09 ET, $\nu = -132.83°$, $\mathbf{B}\cdot\mathbf{R} = 3752.0$ km, $\mathbf{B}\cdot\mathbf{T} = 722.8$ km, Alt. = 965 km, Inbound, 15.9 days to T59											
OTM-206	T58+4d	12-Jul-2009 16:22	131.44	89.42	3.518	290.37	−3.74	3.513	290.46	−3.67	MEA
OTM-207	T58∼apo	17-Jul-2009 15:52	173.71	47.22	0.032	268.48	−35.16	0.032	268.12	−35.06	RCS
OTM-208	T59−3d	21-Jul-2009 15:36	−165.25	26.17	..... CANCELLED						
Titan-59 (T59): 24-Jul-2009 15:35:09 ET, $\nu = -141.14°$, $\mathbf{B}\cdot\mathbf{R} = 3682.3$ km, $\mathbf{B}\cdot\mathbf{T} = 981.6$ km, Alt. = 955 km, Inbound, 15.9 days to T60											
OTM-209	T59+4d	28-Jul-2009 15:21	144.44	70.21	6.296	301.19	22.90	6.294	301.30	22.91	MEA
OTM-210	T59∼apo	01-Aug-2009 22:35	172.97	41.78	0.022	258.38	−21.01	0.023	258.07	−20.88	RCS
OTM-211	T60−3d	06-Aug-2009 22:05	−165.55	20.31	..... CANCELLED						
Titan-60 (T60): 09-Aug-2009 14:04:59 ET, $\nu = -148.00°$, $\mathbf{B}\cdot\mathbf{R} = 3613.3$ km, $\mathbf{B}\cdot\mathbf{T} = 1257.7$ km, Alt. = 970 km, Inbound, 15.9 days to T61											
OTM-212	T60+4d	13-Aug-2009 21:49	154.71	55.31	..... CANCELLED						
OTM-213	T60∼apo	16-Aug-2009 14:04	169.58	40.44	13.004	335.23	60.76	13.002	335.22	60.75	MEA
OTM-214	T61−3d	22-Aug-2009 03:34	−170.41	20.51	..... CANCELLED						
Titan-61 (T61): 25-Aug-2009 12:52:44 ET, $\nu = -144.99°$, $\mathbf{B}\cdot\mathbf{R} = 2803.5$ km, $\mathbf{B}\cdot\mathbf{T} = -2593.1$ km, Alt. = 962 km, Inbound, 47.8 days to T62											
OTM-215	T61+4d	29-Aug-2009 13:19	140.45	441.53	0.514	293.68	43.97	0.515	293.89	44.18	MEA
OTM-216	T61∼apo	05-Sep-2009 02:48	171.71	410.29	4.480	300.12	66.44	4.476	300.37	66.52	MEA
OTM-217	T62−3d	09-Oct-2009 11:04	−158.97	20.95	0.150	281.36	−0.94	0.146	280.90	−0.52	RCS
Titan-62 (T62): 12-Oct-2009 08:37:30 ET, $\nu = -143.32°$, $\mathbf{B}\cdot\mathbf{R} = 2318.5$ km, $\mathbf{B}\cdot\mathbf{T} = 3448.4$ km, Alt. = 1300 km, Inbound, 21.0 days to E7											
OTM-218	T62+4d	16-Oct-2009 00:34	145.55	268.34	0.851	222.45	65.44	0.844	222.49	65.70	MEA
OTM-219	T62∼apo	21-Oct-2009 00:04	172.13	241.77	4.169	21.91	68.09	4.162	22.23	68.07	MEA
OTM-220	E7−3d	29-Oct-2009 23:35	−157.31	211.22	0.068	306.76	0.62	0.067	306.46	0.93	RCS
Enceladus-7 (E7): 02-Nov-2009 07:43:04 ET, $\nu = 53.70°$, $\mathbf{B}\cdot\mathbf{R} = 308.3$ km, $\mathbf{B}\cdot\mathbf{T} = 160.2$ km, Alt. = 100 km, Outbound, 18.8 days to E8											
OTM-221	E7+3d	05-Nov-2009 09:20	157.16	148.71	0.312	243.46	−10.79	0.303	243.80	−10.21	MEA
OTM-222	E7∼apo	12-Nov-2009 09:06	−178.11	123.97	..... CANCELLED						
OTM-223	E8−3d	17-Nov-2009 22:37	−157.65	103.51	..... CANCELLED						
Enceladus-8 (E8): 21-Nov-2009 02:10:56 ET, $\nu = -54.17°$, $\mathbf{B}\cdot\mathbf{R} = 1606.2$ km, $\mathbf{B}\cdot\mathbf{T} = 920.7$ km, Alt. = 1604 km, Inbound, 20.9 days to T63											
OTM-224	E8+2d	22-Nov-2009 22:22	144.35	361.27	2.556	89.04	−7.34	2.553	89.07	−7.54	MEA
OTM-225	E8∼apo	04-Dec-2009 07:39	−169.29	314.86	0.202	146.22	−4.59	0.199	146.65	−4.90	RCS
OTM-226	T63−3d	08-Dec-2009 21:24	−139.09	284.69	..... CANCELLED						
Titan-63 (T63): 12-Dec-2009 01:04:20 ET, $\nu = 148.82°$, $\mathbf{B}\cdot\mathbf{R} = -2214.9$ km, $\mathbf{B}\cdot\mathbf{T} = -7395.0$ km, Alt. = 4850 km, Outbound, 16.0 days to T64											
OTM-227	T63+3d	15-Dec-2009 06:55	170.06	340.98	0.719	100.57	−13.80	0.716	100.46	−13.99	MEA
OTM-228	T63∼apo	20-Dec-2009 06:41	−173.42	324.46	2.231	339.62	−66.22	2.225	339.32	−66.04	MEA
OTM-229	T64−3d	24-Dec-2009 20:26	−145.66	296.73	..... CANCELLED						
Titan-64 (T64): 28-Dec-2009 00:18:05 ET, $\nu = 151.21°$, $\mathbf{B}\cdot\mathbf{R} = -3521.3$ km, $\mathbf{B}\cdot\mathbf{T} = -1470.2$ km, Alt. = 955 km, Outbound, 15.9 days to T65											
OTM-230	T64+3d	31-Dec-2009 05:57	169.26	339.39	..... CANCELLED						
OTM-231	T64∼apo	05-Jan-2010 05:43	−172.58	321.23	8.050	48.84	45.62	8.054	48.80	45.51	MEA
OTM-232	T65−3d	09-Jan-2010 19:29	−141.25	289.89	0.036	181.85	12.38	0.035	181.76	12.12	RCS
Titan-65 (T65): 12-Jan-2010 23:11:42 ET, $\nu = 151.19°$, $\mathbf{B}\cdot\mathbf{R} = 3602.4$ km, $\mathbf{B}\cdot\mathbf{T} = 1579.1$ km, Alt. = 1073 km, Outbound, 16.0 days to T66											
OTM-233	T65+3d	16-Jan-2010 04:59	170.04	341.08	2.270	89.37	30.84	2.266	89.48	30.56	MEA
OTM-234	T65∼apo	21-Jan-2010 04:45	−173.48	324.59	6.072	49.83	51.44	6.075	49.87	51.32	MEA
OTM-235	T66−3d	25-Jan-2010 18:16	−146.18	297.29	..... CANCELLED						
Titan-66 (T66): 28-Jan-2010 22:29:55 ET, $\nu = 149.84°$, $\mathbf{B}\cdot\mathbf{R} = 5914.6$ km, $\mathbf{B}\cdot\mathbf{T} = 8499.3$ km, Alt. = 7490 km, Outbound, 32.8 days to R2											
OTM-236	T66+3d	01-Feb-2010 04:01	167.87	436.50	6.203	202.60	11.92	6.197	202.58	12.05	MEA
OTM-237	T66∼apo	23-Feb-2010 16:33	−176.39	60.41	0.015	260.82	−50.79	0.016	260.71	−50.76	RCS
OTM-238	R2−3d	27-Feb-2010 16:19	−161.39	45.43	..... CANCELLED						
Rhea-2 (R2): 02-Mar-2010 17:41:42 ET, $\nu = -115.92°$, $\mathbf{B}\cdot\mathbf{R} = -700.5$ km, $\mathbf{B}\cdot\mathbf{T} = -509.3$ km, Alt. = 100 km, Inbound, 33.9 days to T67											
OTM-239	R2+8d	11-Mar-2010 01:34	177.03	394.53	..... CANCELLED						
OTM-240	R2∼apo	26-Mar-2010 14:19	170.31	97.51	3.002	64.46	−56.73	3.002	64.32	−56.84	MEA
OTM-241	T67−3d	02-Apr-2010 13:49	−167.52	75.35	0.034	111.86	26.45	0.034	112.11	26.30	RCS
Titan-67 (T67): 05-Apr-2010 15:51:59.8 ET, $\nu = -146.53°$, $\mathbf{B}\cdot\mathbf{R} = 4778.4$ km, $\mathbf{B}\cdot\mathbf{T} = -9128.6$ km, Alt. = 7438 km, Inbound, 1.6 days to D2											
Dione-2 (D2): 07-Apr-2010 05:17:17 ET, $\nu = -86.96°$, $\mathbf{B}\cdot\mathbf{R} = -468.4$ km, $\mathbf{B}\cdot\mathbf{T} = 952.1$ km, Alt. = 500 km, Inbound, 20.8 days to E9											
OTM-242	D2+4d	10-Apr-2010 23:19	156.49	244.06	9.042	271.97	−85.14	9.044	272.50	−85.08	MEA
OTM-243	D2∼apo	18-Apr-2010 12:33	−177.83	218.39	0.045	113.28	−2.86	0.045	113.55	−3.04	RCS
OTM-244	E9−3d	24-Apr-2010 22:18	−153.56	194.12	..... CANCELLED						
Enceladus-9 (E9): 28-Apr-2010 00:11:23 ET, $\nu = 40.39°$, $\mathbf{B}\cdot\mathbf{R} = 307.0$ km, $\mathbf{B}\cdot\mathbf{T} = 162.7$ km, Alt. = 100 km, Outbound, 20.2 days to E10											
OTM-245	E9+2d	29-Apr-2010 11:47	139.73	363.09	5.714	93.31	−8.65	5.716	93.21	−8.68	MEA
OTM-246	E9∼apo	11-May-2010 11:01	−170.61	313.32	8.884	40.64	67.97	8.881	40.638	67.97	MEA
OTM-247	T68−4d	16-May-2010 04:31	−146.86	289.57	..... CANCELLED						
Enceladus-10 (E10): 18-May-2010 06:05:45.4 ET, $\nu = -39.99°$, $\mathbf{B}\cdot\mathbf{R} = 570.6$ km, $\mathbf{B}\cdot\mathbf{T} = -382.4$ km, Alt. = 439 km, Inbound, 1.9 days to T68											
Titan-68 (T68): 20-May-2010 03:25:26 ET, $\nu = 147.65°$, $\mathbf{B}\cdot\mathbf{R} = 3960.9$ km, $\mathbf{B}\cdot\mathbf{T} = -1577.8$ km, Alt. = 1400 km, Outbound, 16.0 days to T69											
OTM-248	T68+3d	23-May-2010 10:15	169.88	340.13	0.852	107.08	−33.60	0.845	106.80	−33.71	MEA
OTM-249	T68∼apo	28-May-2010 09:44	−173.04	323.05	10.767	82.31	−82.85	10.766	81.83	−82.85	MEA
OTM-250	T69−3d	01-Jun-2010 19:44	−146.10	296.12	0.037	162.29	9.80	0.036	162.45	9.58	RCS
Titan-69 (T69): 05-Jun-2010 02:27:33 ET, $\nu = 151.45°$, $\mathbf{B}\cdot\mathbf{R} = -4632.2$ km, $\mathbf{B}\cdot\mathbf{T} = -1621.0$ km, Alt. = 2044 km, Outbound, 16.0 days to T70											

* Total $\Delta\mathbf{V}$ (burn + turns) expressed in Earth Mean Equator and Equinox of J2000.0 coordinates (EME2000).

at the time of the maneuver (e.g., at a value of 180°, the spacecraft was at apocrone). The central angle for a maneuver is defined as the angle ∠(maneuver location)-Saturn-(target location), measured from the maneuver location to the target location and counting multiple revolutions. Each ΔV listed is the sum of the burn, turns, including the pointing-bias-fix turn for MEA, and ΔVs due to dead-band tightening/limit-cycling for RCS burns. The encounter rows contain the: encounter name, time of closest approach, true anomaly ν, $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, altitude, whether the flyby is inbound/outbound, and days to next encounter.

Out of the 45 planned maneuvers, 31 were performed; 21 of those were implemented with the MEA while 10 used the RCS. Performing maneuvers with the MEA is advantageous because it allows the conservation of the RCS hydrazine propellant.

Table 4 shows the maneuver performance per encounter, comparing the ΔV reconstructed to the planned ΔV. The navigation cost per encounter is the difference between the reference trajectory ΔV, which is deterministic, and the reconstructed ΔV, which is deterministic plus a statistical component. The predicted ΔV statistics per encounter span were garnered from statistical analysis reported in Ref. 11 and 12. Most ΔV costs per encounter were less than 0.5 m/s, but three encounter legs, T63–T64, T65–T66, and T68–T69, were higher. The first two of these trajectory legs had a higher cost because XYZ targeting were used for an ansa-to-ansa observation and an Enceladus plume occultation. Also, it had been a few orbits since a Titan flyby, and the miss at E8 was intentional (see Section VII.C). This led to a larger initial orbit determination uncertainty for the T63–T64 arc, and the larger flyby error at T63 led to the higher ΔV costs. Finally, the T68–T69 cost can be attributed to the ∼2 km T68 flyby error, which required OTM-248 to be over 0.8 m/s, as compared to the near-zero reference trajectory value.

Table 4: Maneuver Performance per Encounter

Encounter Span	Ref. Traj. Det. ΔV (m/s)	Predicted ΔV Statistics Mean (m/s)	1-σ (m/s)	95% (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Navigation ΔV Cost* (m/s)
T58–T59	3.536	3.649	0.127	3.890	3.550	3.545	0.009
T59–T60	6.324	6.642	0.163	6.937	6.318	6.317	−0.007
T60–T61	13.023	13.309	0.259	13.810	13.004	13.002	−0.021
T61–T62	4.739	5.415	0.556	6.535	5.144	5.136	0.397
T62–E7	4.689	5.229	0.464	6.086	5.088	5.073	0.385
E7–E8	0.025	1.015	0.590	2.147	0.312	0.303	0.278
E8–T63	2.397	3.197	0.568	4.284	2.758	2.752	0.356
T63–T64	2.268	2.511	0.230	2.965	2.950	2.941	0.673
T64–T65	8.135	8.412	0.311	9.031	8.086	8.089	−0.046
T65–T66	6.897	8.119	0.624	9.396	8.342	8.341	1.444
T66–R2	6.143	6.184	0.046	6.264	6.218	6.213	0.070
R2–T67/D2	2.630	2.999	0.464	3.965	3.036	3.036	0.406
D2–E9	9.190	9.175	0.054	9.269	9.086	9.089	−0.101
E9–E10/T68	14.621	14.705	0.126	14.919	14.598	14.597	−0.024
T68–T69	11.053	11.834	0.588	12.998	11.656	11.647	0.594

* Navigation ΔV cost = total reconstructed ΔV - total reference trajectory deterministic ΔV

The average navigation ΔV cost per flyby is summarized in Table 5. If we exclude the anomalous high ΔV cost from the T46–T47 encounter due to the large underburn of OTM-169,[9] then the average cost per encounter and the standard deviation are lower for the Equinox Mission than for the Prime Mission. This can be attributed to a well-maintained and operated spacecraft, more accurate satellite ephemerides, and a better Gates model, despite a higher frequency of flybys.

Table 5: Average Navigation ΔV Cost per Flyby

Mission	Flyby Span	Number of Flybys	Navigation ΔV Cost Average (m/s)	Navigation ΔV Cost Std. Dev. (m/s)
Prime	Ta–T44	52	0.331	0.603
Equinox	T45–T69	34	0.439	1.009
Equinox (w/o T46–T47)	T45–T69	33	0.279	0.424

IV. Maneuver Cancellations

When a maneuver design produces a ΔV less than 9 mm/s, or when there is a small mission ΔV cost (or saving), we conduct analysis for maneuver cancellation and/or target biasing (see Section VII.A). Cancellation of a maneuver is favored because it reduces spacecraft use and ground-system stress, but only takes place if certain conditions are met.

Specifically, consideration is given to maneuver size and whether cancellation of a maneuver is: allowable to stay on tour, acceptable given changes to the trajectory and the next target asymptote, and satisfactory for navigation pointing and science requirements. We also review the effects to downstream maneuvers and ΔV penalties. We have developed a streamlined procedure to address the maneuver cancellation analysis since this has become so frequently reviewed in operations. Details of this maneuver cancellation process can be found in Ref. 17.

Table 6 highlights all of the cancelled maneuvers from the past year of the Equinox Mission. In the past year, 14 of the 45 maneuvers covered in the paper were cancelled, 10 statistical maneuvers and 4 deterministic ones. Three cleanup maneuvers were cancelled because it was found that the apocrone maneuver could perform the B-plane change by itself (see OTMs 212, 230, and 239). For OTM-222 the reverse was true, and we performed only the cleanup maneuver (OTM-221). Joint analysis of OTM-222 and OTM-223 showed that neither maneuver needed to be executed.

Table 6: Cancelled Maneuver Summary (OTM-208 to OTM-247)

Maneuver	Burn Type	Description	Orbit Location	Total ΔV Magnitude (m/s)	Cancellation ΔV Cost* (m/s)
OTM-208†	RCS	approach	T59−3d	0.015	−0.093
OTM-211†	RCS	approach	T60−3d	0.017	−0.063
OTM-212	RCS	cleanup	T60+4d	0.026	−0.007
OTM-214†	RCS	approach	T61−3d	0.015	0.116
OTM-222	RCS	apocrone	E7∼apo	0.023	−0.037
OTM-223	RCS	approach	E8−3d	0.121	−0.034
OTM-226†	RCS	approach	T63−3d	0.016	0.119
OTM-229†	RCS	approach	T64−3d	0.015	0.213
OTM-230	MEA	cleanup	T64+3d	1.116	0.104
OTM-235	RCS	approach	T66−3d	0.014	−0.053
OTM-238†	RCS	approach	R2−3d	0.016	0.123
OTM-239	MEA	cleanup	R2+8d	1.536	−1.554
OTM-244†	RCS	approach	E9−3d	0.015	−0.009
OTM-247†	RCS	approach	T68−4d	0.020	−0.135

* Downstream cost through the next 3 to 5 flybys, including maneuver being cancelled. A negative value indicates a ΔV savings.

† Maneuver size was increased to an executable size via time-of-flight biasing (see Table 10).

The cancellation of OTM-229 came about as a result of an accurate execution of OTM-228. The ΔV cost listed in the table was also all in the next encounter leg, which had a large deterministic maneuver in it, and so the cancellation of OTM-229 was not likely to change the anticipated strategy for OTM-230, which was to combine it into OTM-231. OTM-230 was cancelled also.

OTM-239 was the second-largest maneuver ever cancelled for Cassini behind only OTM-001. It was cancelled after we found that the cost to return to the reference trajectory and preserve the T67/D2 double flyby geometry using both OTM-239 and OTM-240 was about 1.5 m/s. See Section V.A for more information.

V. Double Flybys

A "double flyby" occurs when the spacecraft encounters two satellites with no maneuvers between them. The Equinox Mission had two double flybys in the past year, both of which required special analysis by the maneuver team, details of which are reported in Ref. 18. The T67/D2 double flyby was followed by a 100-km Enceladus encounter (E9), which was succeeded by the E10/T68 double flyby. Figure 4 shows the maneuver and flyby locations around the two double flybys T67/D2 and E10/T68.

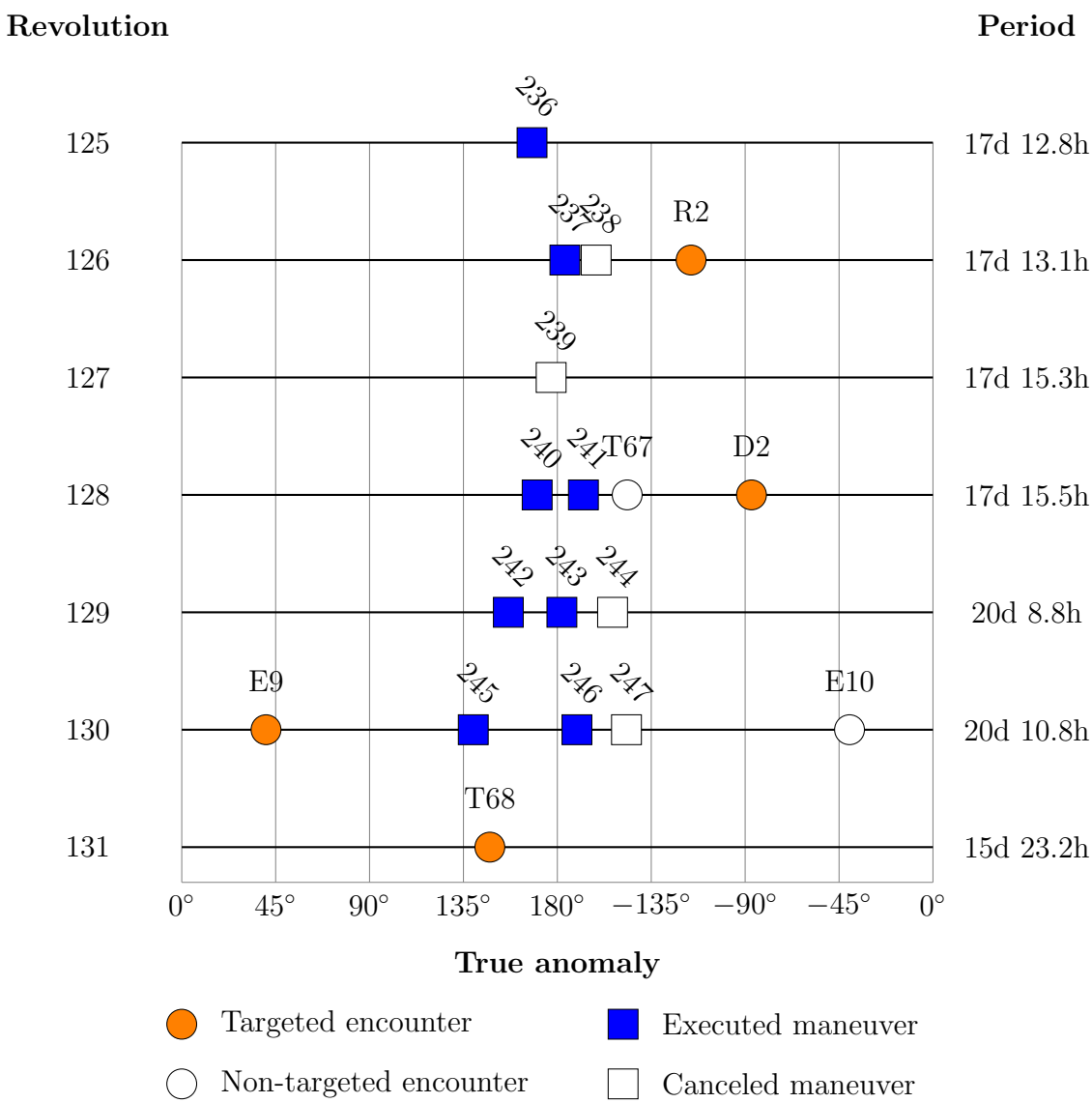


Figure 4: Architecture of Encounters R2, T67/D2, E9, and E10/T68.

V.A. Titan-67/Dione-2

After the Rhea flyby on March 2, 2010, there were three maneuvers allocated for setting up the T67/D2 double flyby (Fig. 5): OTMs 239, 240, and 241. There was a larger than expected miss at Rhea-2 (R2) due to ephemeris error, which moved Cassini farther from the reference trajectory. This miss increased the size of OTM-239. Since it is possible to explicitly target only one of the flybys, the other one must be checked to see if its geometry remains acceptable. We therefore analyzed the first maneuver in this leg, OTM-239, in conjunction with OTM-240. This adds the nuance of seeing whether using XYZ targeting or optimizing the OTM-240 position for a lower ΔV (called "chaining" the maneuvers) would be more desirable. The nominal strategy was to target OTM-239 to the XYZ position of OTM-240, and OTM-240 to the T67 encounter. This strategy would put Cassini exactly on the reference trajectory and as a result achieve the reference trajectory conditions for the T67/D2 double flyby. Because this method required nearly 1.5 m/s more than targeting OTM-240 to either D2 or T67, as seen in Table 7, it was deemed too expensive.

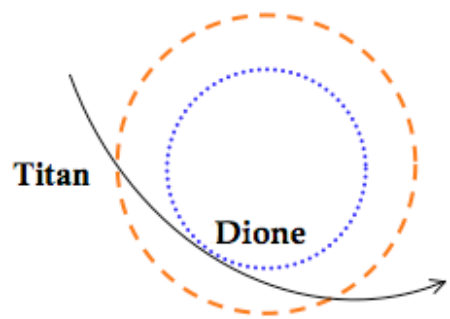


Figure 5: Trajectory Illustration for the T67/D2 Double Flyby.

Table 7: OTM-239 Effects to T67/D2 Double Flyby

	Reference Trajectory	*Nominal Strategy:* OTM-239 target OTM-240 XYZ (Target T67/D2)	*Alternate Strategy 1:* Cancel OTM-239, OTM-240 target T67	*Alternate Strategy 2:* Cancel OTM-239, OTM-240 target D2
Titan-67 (T67)				
Altitude (km)	7461.91	7461.91	7462.01	7437.77
Altitude Diff. (km)	–	2e-3	0.10	−24.13
TCA (ET SCET)	05-Apr-2010 15:51:44	05-Apr-2010 15:51:44	05-Apr-2010 15:51:44	05-Apr-2010 15:51:59
TCA Diff. (sec)	–	−4e-7	2e-7	15.46
Dione-2 (D2)				
Altitude (km)	504.03	503.99	541.41	504.03
Altitude Diff. (km)	–	−0.05	37.38	1e-4
TCA (ET SCET)	07-Apr-2010 05:17:16	07-Apr-2010 05:17:16	07-Apr-2010 05:16:53	07-Apr-2010 05:17:16
TCA Diff. (sec)	–	−0.45	−23.86	1e-5
ΔV Cost vs. Nominal Strategy (m/s)			−1.554	−1.528

The cost of XYZ targeting was so high because of the miss at the R2 flyby. We also showed that attempting to chain the maneuvers caused the optimizer to put almost no ΔV into OTM-239 and all of it into OTM-240. Note that the reference trajectory had OTMs 239 and 240 as deterministic maneuvers both around 1 m/s, so the miss at R2 had changed the trajectory enough that we had to target either D2 or T67, for which the optimum placement of ΔV was all in OTM-240. The science team noted that targeting to Dione was more desirable because the observations there were more sensitive to deviations from the reference trajectory, and there was a Janus observation which would be missed if T67 were targeted. Also, the deviations at T67 resulting from targeting D2 were acceptable because this was a high Titan flyby (7462 km altitude) and the difference was 24 km lower when targeting D2, versus the D2 flyby (504 km altitude) being 37 km higher when targeting T67. The project decided to cancel OTM-239 and target D2 with OTM-240 only (see alternate strategy 2 in Table 7). The statistical maneuver OTM-241 was still required to correct the D2 approach asymptote.

V.B. Enceladus-10/Titan-68

The third and final double flyby of the Equinox Mission was E10/T68 (Fig. 6). The first maneuver in this trajectory leg was OTM-245, which was placed only 36 hours after the Enceladus-9 (E9) flyby instead of the typical 3 days after an encounter. The preliminary analysis thus had to be done before the E9 flyby and the final analysis just after the flyby.

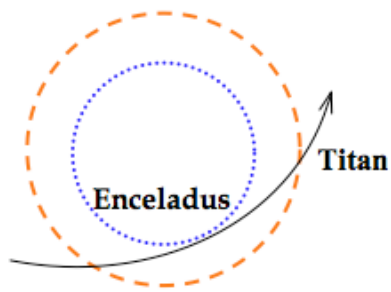


Figure 6: Trajectory Illustration for the E10/T68 Double Flyby.

Table 8 presents the strategies examined during the analysis of OTM-245. Like the T67/D2 flyby, the nominal strategy was to have OTM-245 do XYZ targeting to OTM-246 and then have OTM-246 target to the T68 flyby. This was compared to the strategies of having OTM-246 instead target the E10 flyby, and having OTM-245 chained with OTM-246 and target T68. Comparing the first two strategies of XYZ targeting OTM-246 was worthwhile because they produced a slight difference in the incoming asymptote of the Enceladus encounter (E10). This asymptote difference increased the Titan flyby altitude by 9 km, producing less gravity assist ΔV from Titan, so that the next cleanup maneuver, OTM-248, would increase from 0.04 m/s to about 2 m/s. The effect of this asymptote difference increased OTM-251, the next cleanup maneuver, from almost zero to about 1.5 m/s. The next alternate strategy of chaining the two maneuvers together and targeting the T68 encounter resulted in a predicted downstream total ΔV that was essentially the same as the nominal strategy, but with unacceptable asymptote differences. The E10 flyby would have been too far from the reference trajectory both in altitude and time of closest approach. As there were many sensitive science observations planned around the double flyby, such as a solar occultation prior to E10 (see Section VI), using the option of chaining the maneuvers together was no longer considered due to the large trajectory deviations it produced. Because of the growth in the downstream ΔV for targeting E10 versus T68, and a desire to stay as close to the reference trajectory as possible, we decided to retain the nominal strategy.

Table 8: OTM-245 Effects to E10/T68 Double Flyby

	Reference Trajectory	*Nominal Strategy:* OTM-245 target OTM-246 XYZ (Target T68)	*Alternate Strategy 1:* OTM-245 target OTM-246 XYZ (Target E10)	*Alternate Strategy 2:* Chain OTMs 245 & 246 (Target T68)
Enceladus-10 (E10)				
Altitude (km)	438.85	437.73	438.85	423.93
Altitude Diff. (km)	–	−1.12	−5e-5	−14.92
TCA (ET SCET)	18-May-2010 06:05:46	18-May-2010 06:05:45	18-May-2010 06:05:46	18-May-2010 06:05:44
TCA Diff. (sec)	–	−0.09	2e-6	−1.60
Titan-68 (T68)				
Altitude (km)	1400.00	1400.00	1409.38	1400.00
Altitude Diff. (km)	–	5e-4	9.38	−2e-3
TCA (ET SCET)	20-May-2010 03:25:26	20-May-2010 03:25:26	20-May-2010 03:25:26	20-May-2010 03:25:26
TCA Diff. (sec)	–	1e-6	0.30	1e-6
ΔV Cost vs. Nominal Strategy (m/s)			3.143	0.068

Table 9 shows the analysis done for OTM-246 after OTM-245 to look into targeting either E10 or T68 for the prime and the backup maneuvers. This analysis revealed E10 targeting to be more costly than the pre-OTM-246 estimate due to OTM-245 execution error. While the maneuver itself did not notably change, the downstream ΔV went up by 4.3 m/s, and the deviation increased much more after the T68 flyby. By comparison, the T68 targeting strategy produced an E10 altitude which was only 0.5 km higher than the reference altitude. For the backup maneuvers, the effect that each strategy had on the other flyby was enhanced. The backup targeting T68 had an E10 flyby 54 km lower and 5.5 seconds earlier than nominal. The backup targeting to E10 had T68 121 km higher and 16.4 seconds later than nominal. The ΔV costs for both were higher than their respective prime maneuvers, the T68 one only 0.2 m/s higher, but the E10 one 6 m/s higher. The final decision targeted OTM-246 to T68.

Table 9: OTM-246 Effects to E10/T68 Double Flyby (Post OTM-245)

	Reference Trajectory	*Nominal Strategy:* OTM-246 target T68	*Alternate Strategy 1:* OTM-246 target E10	*Alternate Strategy 2:* OTM-246-BU target T68	*Alternate Strategy 3:* OTM-246-BU target E10
Enceladus-10 (E10)					
Altitude (km)	438.85	439.41	438.85	384.80	438.85
Altitude Diff. (km)	–	0.56	−4e-5	−54.05	9e-6
TCA (ET SCET)	18-May-2010 06:05:46	18-May-2010 06:05:45	18-May-2010 06:05:46	18-May-2010 06:05:40	18-May-2010 06:05:46
TCA Diff. (sec)	–	−0.10	0.0	−5.48	−1e-5
Titan-68 (T68)					
Altitude (km)	1400.00	1400.00	1407.19	1399.99	1521.47
Altitude Diff. (km)	–	5e-4	7.19	−8e-3	121.47
TCA (ET SCET)	20-May-2010 03:25:26	20-May-2010 03:25:26	20-May-2010 03:25:26	20-May-2010 03:25:26	20-May-2010 03:25:42
TCA Diff. (sec)	–	1e-6	−0.29	1e-6	16.41
ΔV Cost vs. Nominal Strategy (m/s)			4.334	0.192	10.406

VI. Occultations

Many occultations were planned to occur during the last year of the Equinox Mission. These observations were planned with the reference trajectory, and when it came time to perform the maneuvers in the trajectory leg that contained them, they became an additional factor in the design and analysis of the maneuvers.

The first of these occultations was the ansa-to-ansa occultation on December 25, 2009. The maneuvers before this occultation were OTMs 227, 228, and 229. For this trajectory leg, the occultation took place between OTM-229 and pericrone (Saturn periapsis), so the trajectory work for this observation started with OTM-227. The nominal strategy chosen was to have OTM-227 XYZ target OTM-228, yielding a position deviation at the occultation of a few kilometers. The first alternate strategy considered was to cancel OTM-227 and combine it with OTM-228, but this cost 0.7 m/s ΔV and the deviation grew to 500 km. The alternate strategy was to chain OTM-227 and OTM-228 together, which saved a negligible amount of ΔV (on the order of mm/s) compared to the nominal strategy, and the deviation was about 125 km. Given that the cost was essentially the same for the XYZ targeting and the deviations with this strategy were the smallest and best for the occultation, the nominal plan was executed for OTM-227.

On January 26, 2010, there was a second ansa-to-ansa occultation preceded by an Enceladus plume occultation only 2 hours earlier; OTMs 233–235 were the maneuvers before the event. For this trajectory leg, we examined three alternate strategies for OTM-233 in addition to the baseline strategy of doing XYZ targeting to OTM-234. The nominal strategy produced a plume occultation about 51.5 km above the surface of Enceladus. The first alternate strategy cancelled OTM-233 and targeted T66 with only OTM-234, but this was quickly dismissed because the resulting trajectory missed the plume occultation. The next strategy was to chain OTM-233 and OTM-234 together, which was predicted to save nearly 1 m/s of ΔV, but that saving would not be realized until the next leg after the T66 flyby, and was subject to maneuver execution and flyby errors. This strategy also produced a plume occultation only 2.9 km above the surface of Enceladus, which when combined with the uncertainty on the occultation direction of about 7 km (1σ) made that option unacceptable to the science team. The final alternate was based on finding the best XYZ target for OTM-233 which would produce a plume occultation closest to the reference trajectory value of 20 km. We found that it was possible to have an occultation at 25 km altitude and save 0.8 m/s ΔV downstream. However, that saving was also not considered realizable for the same reasons as above. Also, the science team was not comfortable with going this low. We decided to perform OTM-233 by doing XYZ targeting to OTM-234, which had the 51.5 km predicted plume occultation altitude. This also lent itself to another point which was expressed by the science team, which was that the ansa-to-ansa occultation shortly after was more important to get, so being as close as possible to the reference trajectory was of the most importance.

On May 18, 2010, there was a solar plume occultation for E10. As the cleanup maneuver in the trajectory leg leading up to this encounter was targeting the reference trajectory Cartesian position of OTM-246, the trajectory deviations were already very low. With OTM-246 being the last deterministic maneuver before this occultation, we needed to look at the change in the occultation altitude for each strategy to find the best option. The reference trajectory had an occultation altitude of 15.1 km. The nominal strategy of targeting to T68 yielded an altitude of 17.4 km, compared to the alternate strategy of targeting E10, which gave an altitude of 15.1 km, same as the reference trajectory. This makes sense as the occultation is very close to the E10 flyby. The backup maneuver was also examined, and we found that the backup targeting E10 was more desirable as it had an altitude of 16.5 km compared to the 37.1 km for the T68-targeted strategy. As explained in the previous section, E10 targeting was ruled out due to high downstream ΔV penalty.

VII. Biased Targets

Occasionally, one or more of the targeting conditions to an encounter ($\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and TF), defined in the reference trajectory, are altered, thereby changing the respective targeting maneuvers. These changes fall into either one of two categories: time-of-flight biasing and target biasing. Time-of-flight biasing involves the inflation of a small RCS maneuver to an executable range (typically 10 mm/s), all by changing the time of closest approach of the upcoming flyby. This is described in detail in the forthcoming section. Target biasing entails the change of one or both spatial components of the B-plane, $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$. This strategy is recommended by the maneuver team whenever a substantial downstream ΔV saving can be realized by a small change in the target, without sacrificing any downstream science activities. Over time, asymptote errors can grow due to cancelled maneuvers and uncorrected flyby errors. Biasing $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ can bring

the trajectory back to the reference by reducing these accumulated asymptote errors and at the same time provide opportunities to cancel further downstream maneuvers.

VII.A. Time-of-Flight Biasing

While this strategy was never implemented during the last year of the Equinox Mission, time-of-flight biasing was studied for a number of the approach maneuvers. For maneuvers whose unbiased ΔV magnitude is smaller than 9 mm/s, time-of-flight biasing is a way to increase the ΔV magnitude to an amount which can be implemented by the spacecraft with minimal deviation from the target. The required bias is estimated by a linear model of the maneuver, $\Delta\mathbf{V} = \mathbf{K}^{-1}\Delta\mathbf{B}$. With $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ fixed, the ΔV magnitude becomes a quadratic equation in terms of time of flight.[7] Of the two time-of-flight shift solutions for ΔV, the smaller of the two shifts was generally chosen. This can be seen in Table 10, where the first computed option is the one that is closer to the nominal closest approach time. The original ΔV was used to find the time-of-flight bias solutions. In most cases, this ΔV was the first preliminary design that resulted in a maneuver under the 10 mm/s + 5 mm/s deadband-tightening ΔV requirement for execution. The bold font indicates which biased option was chosen, and the other option was chosen for OTM-244 and OTM-247 because the smaller time-biased option resulted in undesirable RWA wheel speeds. The last column represents the final ΔV design based on the chosen time-of-flight bias for the targeted encounter. This design is the total ΔV (burn + turns), including the 5 mm/s deadband-tightening ΔV for RCS burns. All the maneuvers in this table were cancelled, and of the eight maneuvers analyzed, four had a downstream ΔV cost between 0.11 and 0.21 m/s (see Table 6 for cancellation costs).

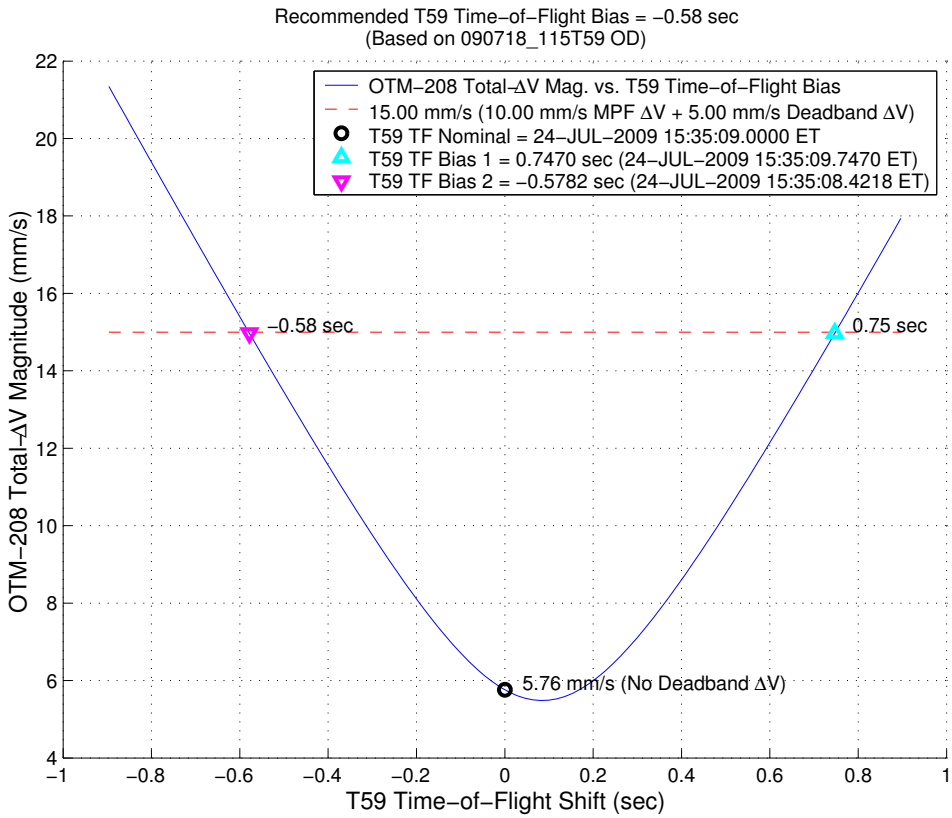
Table 10: Maneuvers Designed with Encounter Time-of-Flight Biases

			Flyby Time-of-Flight Bias			
Approach Maneuver	Flyby	Original ΔV Mag. (mm/s)	Computed Option 1 (sec)	Computed Option 2 (sec)	Chosen Bias (sec)	Biased ΔV Mag. (mm/s)
OTM-208	T59	5.76	**−0.58**	0.75	−0.6	15.37
OTM-211	T60	4.78	**−0.51**	0.73	−0.6	16.61
OTM-214	T61*	7.61	**0.49**	−1.03	0.5	14.97
OTM-226	T63	7.55	**0.14**	−0.67	0.2	15.62
OTM-229†	T64	11.51	**0.12**	−0.80	0.12	14.70
OTM-238	R2	1.94	**0.48**	−0.51	0.5	16.01
OTM-244	E9	3.02	0.39	**−0.45**	−0.45	15.25
OTM-247	T68	11.12	−0.22	**1.41**	1.42	20.26

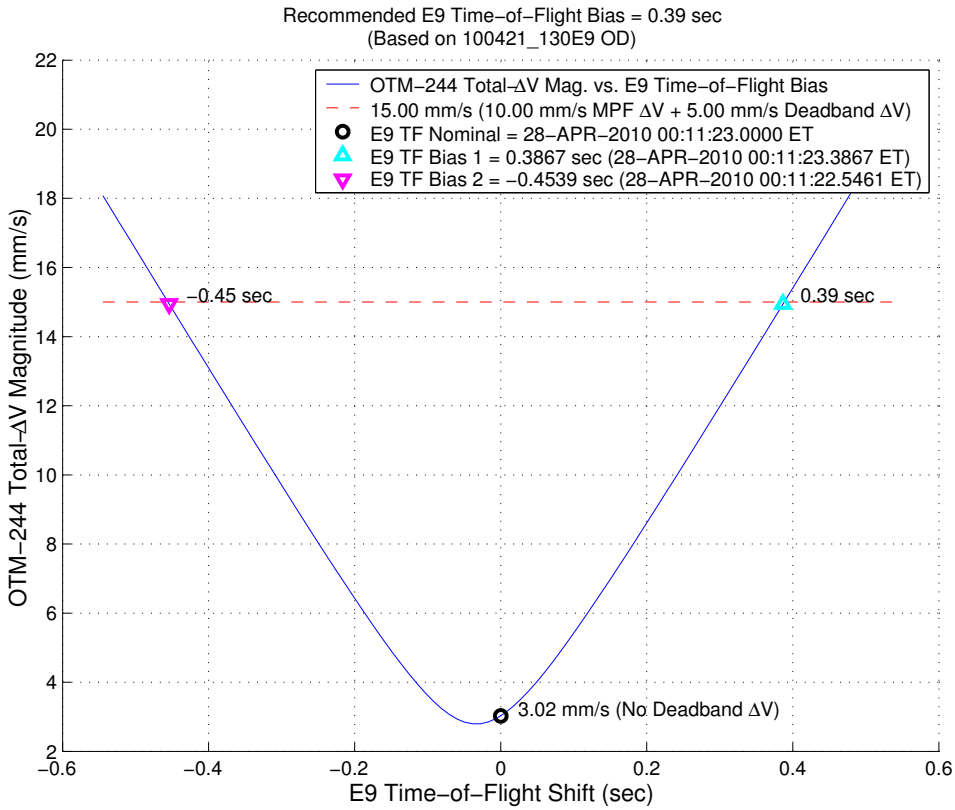
* The T61 flyby was previously biased by +2 km in $\mathbf{B}\cdot\mathbf{R}$ and +14 km in $\mathbf{B}\cdot\mathbf{T}$ via OTM-213 (see Section VII.B).

† The final maneuver design based on the nominal T64 time of closest approach was used to determine the time-of-flight bias solutions.

Figure 7 shows two examples of how the time of flight can be changed to increase the size of a maneuver. The two points where the curve crosses the 15 mm/s dashed line (10 mm/s minimum ΔV + 5 mm/s deadband-tightening ΔV), correspond to the two possible TF shift solutions for bringing the maneuver to an executable range. For the case of OTM-208 (Fig. 7(a)), the recommended T59 TF bias of −0.58 seconds, rounded up to −0.6 seconds in actual operations, was utilized. However, for the case of OTM-244 (Fig. 7(b)), using the recommended E9 TF bias of 0.39 seconds yielded undesirable RWA wheel speeds. The alternate TF bias solution of −0.45 seconds produced better wheel speeds, therefore, was implemented instead. Both designed approach maneuvers were ultimately cancelled since they would not improve on the flyby accuracy and downstream ΔV cost.



(a) Titan-59 (T59) Time-of-Flight Bias via OTM-208 ΔV.

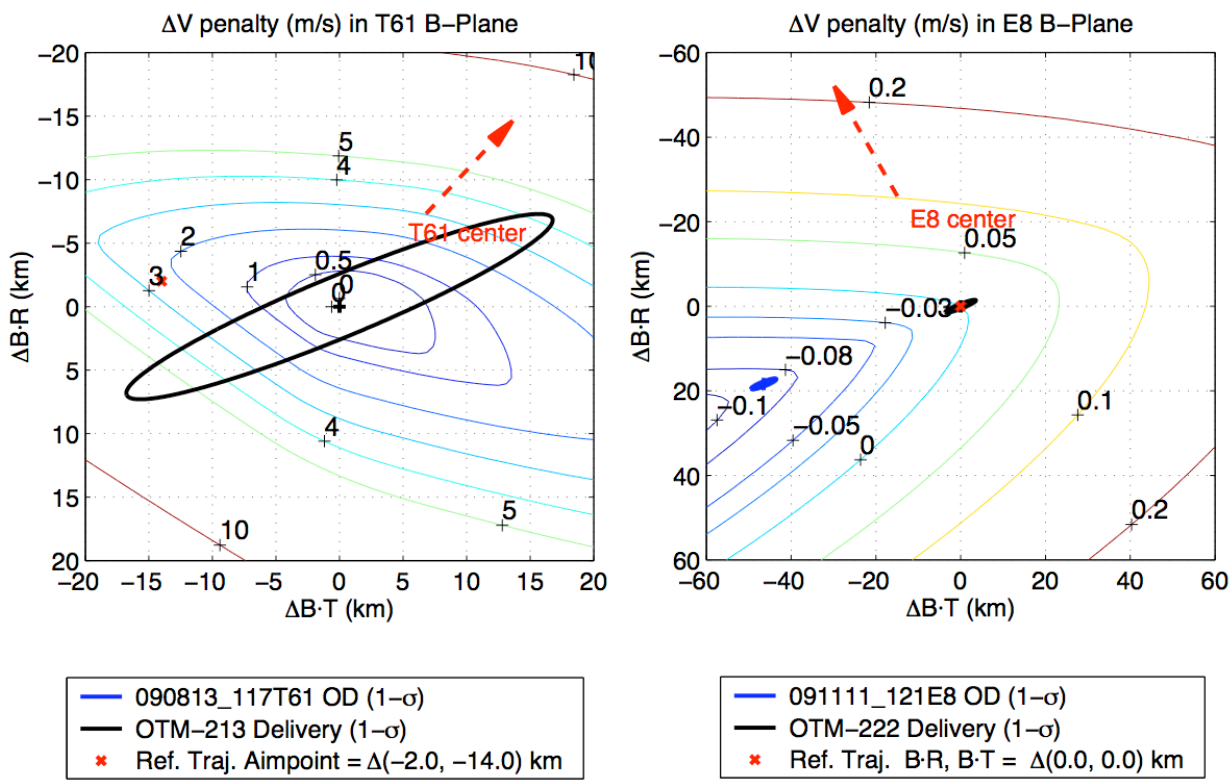


(b) Enceladus-9 (E9) Time-of-Flight Bias via OTM-244 ΔV.

Figure 7: Maneuver ΔV vs. Encounter Time-of-Flight

VII.B. Alternate T61 Targeting via OTM-213

For the T61 flyby we realized that we could save about 2.5 m/s of ΔV if we targeted an aimpoint which was almost 15 km away from the nominal target. Figure 8(a) shows the ΔV contour plot, where the total change comprised about 2 km in $\mathbf{B} \cdot \mathbf{R}$ and 14 km in $\mathbf{B} \cdot \mathbf{T}$. This also lowered the flyby altitude from 970 km to 962 km and increased the probability of impact from 0.5% to 2.0%. As the shift in the aimpoint of OTM-213 was small compared to the shift produced by the maneuver itself, the size of the maneuver stayed about the same at ∼13 m/s. The ΔV saving was achieved from reductions in the sizes of the apoapsis maneuvers targeting to E7, E8, and T63 (OTMs 219, 222, and 225 respectively). Targeting the shifted aimpoint also put the trajectory much closer to the reference trajectory, from a maximum deviation of 2300 km to 1200 km in the T61 to T62 trajectory leg. So, we decided that OTM-213 would target the biased aimpoint and thereby save over 2 m/s of ΔV.



(a) Titan-61 (T61) B-Plane Shift via OTM-213.

(b) Enceladus-8 (E8) B-Plane Shift via OTM-222.

Figure 8: B-Plane Shift vs. ΔV Contours

VII.C. Alternate E8 Targeting via OTM-222 and OTM-223 Cancellations

This was a case where both the apocrone and approach maneuvers were cancelled, OTM-222 and OTM-223, respectively. In this case we actually decided to leave the trajectory alone and let the spacecraft fly by Enceladus on the current trajectory because it was predicted to save a small amount of ΔV. Figure 8(b) shows that the trajectory direction to save ΔV was nearly perpendicular to the direction to Enceladus, such that the flyby altitude was only 7 km lower (nominally 1604 km altitude). The science team believed that they would likely be able to meet their requirements as long as the pointing vectors for their instruments were updated. We decided that if the requirements were found to not be met, that OTM-223 could instead be used to target the nominal E8 aimpoint. With all this in mind, we decided to cancel OTM-222. OTM-223 was also deemed unnecessary, and was subsequently cancelled.

VIII. Concluding Remarks

Navigation for Cassini-Huygens spacecraft during the Equinox Mission proved to be as challenging as the previous 4 years of the Prime Mission. In addition to the normal Titan flybys necessary for fueling the tour, the past year included two double-flybys, six flybys of icy satellites, and several occultations. This paper showcased the most significant efforts by the maneuver team to maintain the trajectory. It compares the pre-planned maneuver designs and their actual implementations. Also, the cancellation maneuver analysis proved to be as extensive as the nominal design work. To put this in perspective, 14 out of 45 maneuvers (a third of the maneuvers for this year) were cancelled. Eight of the 14 cancelled maneuvers were considered for time-of-flight bias which required additional effort.

Overall, with all this activity we were able to maintain the prescribed tour through the successful execution of 31 maneuvers (11 Titans and 6 icy satellites that include Enceladus, Dione, and Rhea).

IX. Acknowledgment

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