(Preprint) AAS 09-349

CASSINI-HUYGENS MANEUVER EXPERIENCE: FIRST YEAR OF 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 cruise, it entered a Saturnian orbit for a four-year, prime mission. Due to the success of the prime mission, spacecraft health, and remaining propellant, a two-year extended mission, the Equinox Mission, was approved. Maneuver designs and analyses performed through the first year of the Equinox Mission are presented. Results for the 46 most recent maneuvers are given. A substantial contribution to the navigation success of the Cassini-Huygens spacecraft is the continued accurate performance, which has exceeded the pre-launch expectations and requirements.

INTRODUCTION

Cassini-Huygens is a robotic spacecraft mission currently studying the planet Saturn and its moons. It is a joint venture of NASA, ESA, and ASI. The Cassini-Huygens spacecraft, see Figure 1, was launched October 15, 1997. After a seven-year cruise, Cassini-Huygens entered orbit around Saturn on July 1, 2004. One of the mission's first accomplishments was the successful delivery of the Huygens probe to Titan, Saturn's largest moon. The Cassini orbiter continued to travel in a series of highly elliptical orbits about Saturn. Cassini has completed its four year primary mission, and due to the success of the prime mission, spacecraft health, and remaining propellant, an extended mission was approved. On July 1, 2008, Cassini began the two-year Equinox Mission. During this mission, Cassini will continue the study of Saturn and its moons as the Sun crosses the plane of Saturn's equator. Light from the Sun will gradually transition from illuminating the the rings from south to north. The mission's goal is an ongoing study of the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites. In addition, Cassini will continue examination of Titan's atmospheric structure, composition, and surface topography. The Equinox Mission includes close flybys of Enceladus, as well as one flyby each of Rhea and Dione.

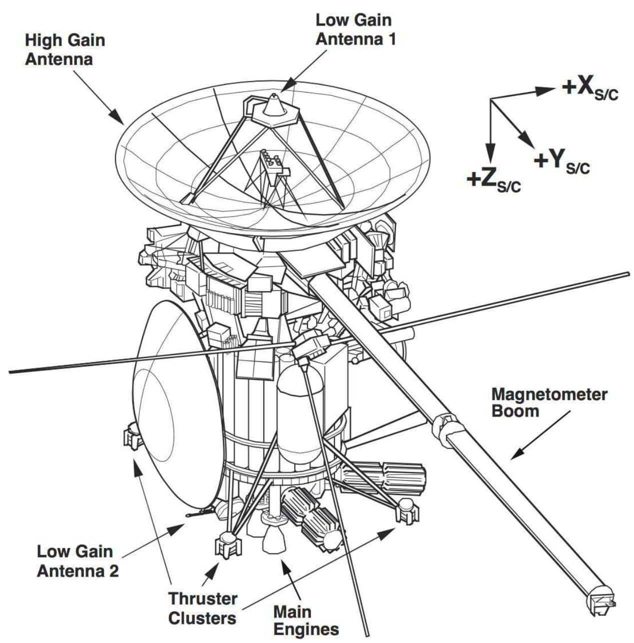

Figure 1. Cassini-Huygens Spacecraft.

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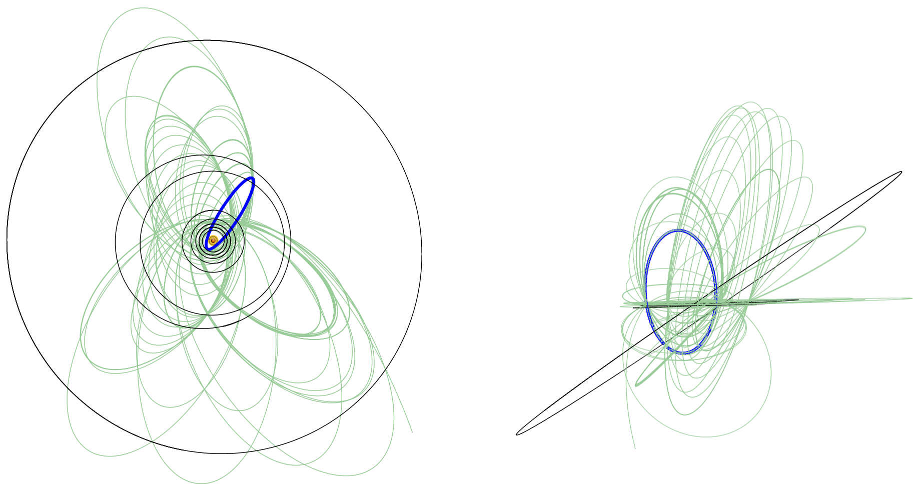
OVERVIEW

Earlier maneuver design papers from the Cassini Navigation Team have reported pre-launch analysis,[1] maneuvers planned and performed during cruise,[2,3,4] and each year of the primary mission,[5,6,7,8] which ended in June 2008. This paper covers the most recent period of exploration of the Saturnian system, the first year of the Equinox Mission, from a maneuver analyst's perspective.

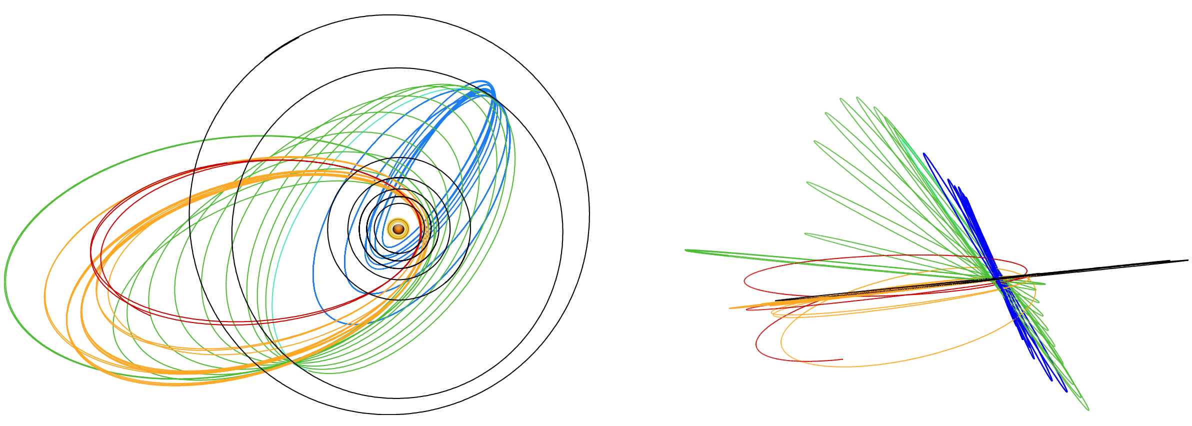
The four-year prime mission consisted of a total of 157 planned Orbit Trim Maneuvers (OTMs), 53 targeted encounters to Titan and other satellites, and 75 orbits of Saturn (shown in gray in Figure 2).



(a) Saturn North Pole (b) Saturn Equatorial View.

Figure 2. Cassini Prime Mission Trajectory. *Last orbit of the prime mission, shown in blue*

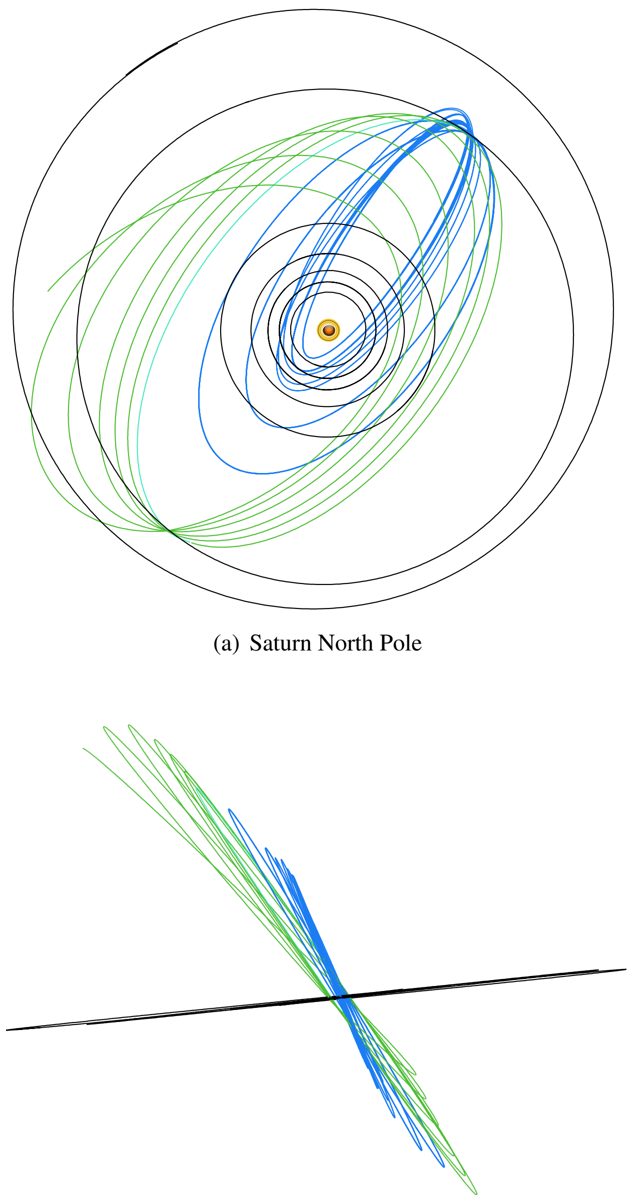
By comparison, the two-year Equinox Mission includes 96 planned OTMs, 35 close flybys of Titan and other icy satellites, and 60 orbits of Saturn as shown in Figure 3.



(a) Saturn North Pole (b) Saturn Equatorial View.

Figure 3. Cassini Equinox Mission Trajectory. *High inclination phase shown in blue; Pi-transfer shown in cyan; Equinox phase shown in green*

At the end of the prime mission, Cassini's orbit was the highest inclination it had ever been with respect to Saturn's equator, 74.7°, and is shown in Figure 2 in blue. Consequently, the Equinox Mission (see Figure 3) began with the Cassini spacecraft in high inclination orbits, (also shown in blue) these orbits provided the best opportunities to use stellar occultations to penetrate the B-ring (with the rings spread out like a halo around Saturn). A pi-transfer (shown in cyan) was used to transition the encounter longitude by 180°. The first year of the Equinox Mission concluded with the first half of the equinox phase, designed to study Saturn as the Sun crosses the plane of Saturns equator (shown in green).



(a) Saturn North Pole

(b) Saturn Equatorial View.

Figure 4. Cassini Trajectory *July 1, 2008 to July 8, 2009*

This paper considers the 46 maneuvers designed to accommodate the 17 most recent encounters, 14 of which were with Titan (Titan-45 (T45) to Titan-58 (T58)) and 3 that were with Enceladus (Enceladus-4 (E4) to Enceladus-6 (E6)). These encounters were planned to allow a variety of Titan science, including Radio Science gravity measurements, occultations, Visible and Infrared Mapping Spectrometer (VIMS) observations, Ion and Neutral Mass Spectrometer (INMS) samplings, and altimetry observations. The targeted flybys of Enceladus in the first year of the Equinox Mission allowed cameras and spectrometers to obtain the highest resolution views of the active south pole region, as well as permitting Cassini to pass through the plumes for in-situ measurements near closest approach and to acquire remote sensing measurements. By the end of the first year of the Equinox Mission, Cassini will be engaged in several months of measurements surrounding Saturn's equinox (August 11, 2009).

MANEUVER EXECUTION

Cassini's propulsion subsystem includes a bipropellant Main Engine Assembly (MEA) for large trajectory corrections and a monopropellant Reaction Control Subsystem (RCS) for small trajectory corrections, attitude control functions, and reaction wheel desaturation (Figure 1). The RCS consists of four hydrazine thruster clusters, a total of eight primary and eight backup thrusters. The thrusters are grouped into two sets. The first set faces the +/- $Y_{S/C}$ spacecraft directions and it is used to make balanced turns about the $Z_{S/C}$ axis (roll turns). The other set faces the -$Z_{S/C}$ axis and it is used to make unbalanced turns about the $X_{S/C}$ axis (pitch turns) and $Y_{S/C}$ axis (yaw turns).

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 nominal attitude. If turns are performed with the RCS thrusters then the yaw turns will impart $\Delta\mathbf{V}$, requiring that turn angles be computed so that the turn and burn $\Delta\mathbf{V}$ sum properly. Turns performed with the Reaction Wheel Assembly (RWA) do not impart $\Delta\mathbf{V}$. Since cruise, maneuvers using the MEA perform an extra turn of 0.9° to correct for a known pointing bias.

The choice of MEA or RCS for a given maneuver is governed by the size of the maneuver. If a maneuver $\Delta\mathbf{V}$ magnitude is greater than about 300 mm/s then the MEA is used, otherwise the RCS is used. Models of the maneuver execution errors are implemented for statistical analysis and preliminary judgments of maneuver performance. These models have been updated occasionally based on maneuver performance thus far in the Saturnian tour.[9,10,11,12]

The maneuver execution-error models are Gates models[13] and account for four independent error sources, fixed and proportional magnitude errors and fixed and proportional pointing errors. Four parameters specify the standard deviations for the error sources and each error source is assumed to have a zero mean. All pointing errors are perpendicular to the nominal $\Delta\mathbf{V}$ vector with an uniform distribution.

The models used over the most recent year are listed in Table 1. The current model, 2008-01, has been in use since OTM-192 in April 2009.[12] It superseded the 2007-02 model,[14] which had been in use since OTM-144's design. The difference between the 2007-02 and 2008-01 models is an update to the MEA terms. The 2008-01 execution-error analysis also resulted in action items to remove the observed magnitude biases (fixed and proportional) in the main engine execution, via flight software patches affecting burn duration, in an effort to mitigate the tendency to underburn.[15]

Table 1. Execution-Error Models *June 2008 - July 2009; given as 1-σ*

		RCS		MEA	
		Fixed	Proportional	Fixed	Proportional
2007-02 (Feb 08)	Magnitude	1.0 mm/s	0.4%	5.0 mm/s	0.02%
	Pointing	0 mm/s	9.0 mrad	3.0 mm/s	0.6 mrad
2008-01 (Jan 09)	Magnitude	1.0 mm/s	0.4%	4.5 mm/s	0%
	Pointing	0 mm/s	9.0 mrad	3.0 mm/s	1.1 mrad

The navigation strategy since launch has been to target the spacecraft to fixed encounter conditions defined in the reference trajectory*.[16] These targeted parameters are three B-plane parameters of an upcoming encounter: the spatial components $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ and the temporal component time-of-flight (TF). (For an explanation of the B-plane, see B-Plane Appendix and Ref. 17). $\mathbf{\Delta B}$ is referred to as the B-plane error ($\Delta\mathbf{B}\cdot\mathbf{R}$, $\Delta\mathbf{B}\cdot\mathbf{T}$, and ΔTF) .

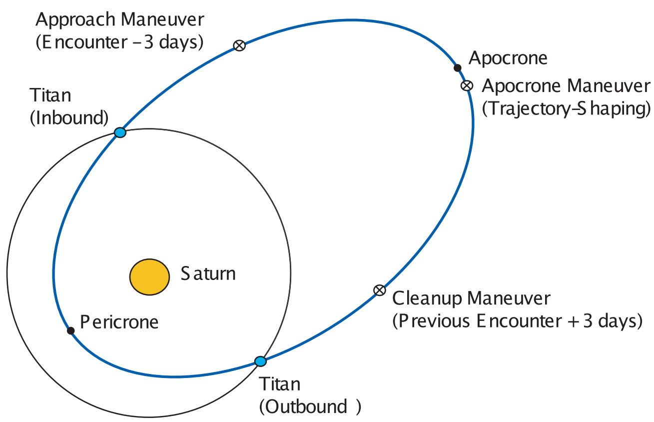


Figure 5. Maneuver Strategy for Saturn Tour *Outbound-to-inbound leg shown. Three maneuver between encounters.*

The navigation team continues to employ a strategy involving three propulsive maneuvers, referred to as OTMs, between each targeted satellite encounter: a flyby-cleanup maneuver and two targeting maneuvers. Past studies have shown that any additional maneuvers between encounters generally do not significantly lower the $\Delta\mathbf{V}$ requirements.[18] Figure 5 illustrates this maneuver strategy for an outbound-to-inbound† Titan transfer. The cleanup maneuver, usually three days after an encounter, corrects trajectory errors from the previous flyby. The maneuver's location depends on the time required to converge the Orbit Determination (OD) estimate used to design the maneuver, the time required to develop the maneuver, and all other processes through the uplinking of its command sequence. The next maneuver targets the encounter directly and is performed near apocrone (Saturn apoapsis) to shape the trajectory in order to achieve the desired flyby conditions. Note, the cleanup maneuver occasionally is used to also shape or to take the place of the apoapsis maneuver in shaping the trajectory. The approach maneuver, the last targeting maneuver, is usually executed three days before an encounter. It has the same target as the shaping maneuver, and is designed to only corrects errors, enabling the mission to achieve as accurate flyby conditions as possible. The approach maneuver location avoids interference with science activities during the encounter period and allows enough time to perform a backup maneuver if necessary. All of the mission's OTMs have backup locations. When a backup is used, the maneuver is said to be delayed.

*The reference trajectory provides predetermined maneuver locations and flyby targets according to science sequence planning and objectives.

†An outbound flyby occurs after pericrone (Saturn periapsis). An inbound encounter occurs before pericrone.

Cleanup maneuvers are often designed with a chained two-impulse optimization strategy, which minimizes the sum of cleanup and shaping maneuvers across several encounters. This optimization technique helps control errors in the outgoing asymptote of hyperbolic satellite flybys without altering downstream flyby aimpoints after each encounter. The cost function for this optimization problem is detailed in several of the previously cited papers.[19]

The reference trajectories serve as the source for estimates of geometry and timing for future events, like a closest-approach to Titan; for maneuver-targeting aimpoints; and as the starting point for OD and maneuver statistical analyses.[20] Updates to the reference trajectory during the tour were primarily made to tweak flyby details or improve some maneuver locations. Such tweaks tended to increase the deterministic $\Delta \mathbf{V}$ cost of the tour. Previous reports show the history of the reference trajectory updates. For the period discussed in this paper, the 080520 reference trajectory was in use.

SUMMARY OF NAVIGATION PERFORMANCE

Table 2 lists the targeted encounter conditions and the achieved flyby differences for each encounter during the first year of the equinox mission, T45 to T58. The $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and time of closest-approach (TCA) target conditions were defined in the reference trajectories and used in the final maneuver designs. The flyby differences from the reference trajectory in Table 2 represent flyby errors for nominally targeted encounters. As such, transfers that include cancelled maneuvers contain differences built in at cancellation as well as those due to flyby errors. Moreover, transfers that include maneuvers with biased targets represent the shifts due to the biasing in addition to the flyby errors.

Table 2. Targeted Encounter History *Titan-45 to Titan-58*

Encounter		$\mathbf{V}_\infty$	Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0)				Flyby Differences from Reference Trajectory‡		
I = Inbound O = Outbound		($\frac{km}{s}$)	B·R (km)	B·T (km)	Time of Closest Approach (ET/SCET)*	Altitude (km)†	B·R (km)	B·T (km)	TCA (s)
T45	O	5.88	3246.45	-3029.17	31-Jul-2008 02:14:16	1613.4	0.61	3e-3	0.03
E4	O	17.73	73.39	291.73	11-Aug-2008 21:07:24	53.5	-0.58	-0.45	-0.11
E5§	O	17.73	68.19	267.25	09-Oct-2008 19:07:45	28.5	0.04	-0.42	0.04
E6	O	17.71	110.18	433.89	31-Oct-2008 17:15:56	200.3	-33.1	-21.2	0.93
T46	O	5.87	1319.98	3698.55	03-Nov-2008 17:36:28	1100.0	-5.92	7.63	-0.13
T47	O	5.86	1533.12	-3531.74	19-Nov-2008 15:57:33	1022.6	0.03	-0.69	-0.11
T48	O	5.86	86.16	-3786.58	05-Dec-2008 14:26:50	960.0	0.15	-0.53	5e-3
T49	O	5.86	2737.62	-2631.62	21-Dec-2008 13:00:57	970.0	0.32	-0.30	0.02
T50	O	5.87	3778.47	-253.61	07-Feb-2009 08:51:57	960.0	6.25	-6.55	0.81
T51	O	5.86	1621.74	-3422.68	27-Mar-2009 04:44:42	960.0	1.74	-2.08	0.28
T52	I	5.54	6416.68	-2827.31	04-Apr-2009 01:48:53	4150.0	-2.12	3.82	-0.47
T53	I	5.54	6194.01	-1837.93	20-Apr-2009 00:21:51	3600.0	-1.86	-1.49	0.04
T54	I	5.54	6010.05	-1071.48	05-May-2009 22:55:21	3244.4	-2.23	-0.21	-0.14
T55	I	5.55	3811.44	-266.33	21-May-2009 21:27:47	965.0	0.53	-0.68	0.08
T56	I	5.55	3818.68	123.32	06-Jun-2009 20:01:06	965.0	2.58	-0.42	0.11
T57	I	5.55	3785.36	439.49	22-Jun-2009 18:33:41	955.0	-0.04	-0.31	0.01
T58	I	5.55	3751.96	722.81	08-Jul-2009 17:05:09	965.0	0.93	-1.40	0.25

* Ephemeris Time (ET) / Spacecraft Event Time (SCET).
† 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 maneuver(s).
§ E5 TCA biased by +0.02 in OTM-166 design.

To compare the maneuver performance per encounter, Table 3 lists the total reference trajectory deterministic $\Delta\mathbf{V}$s (computed by CATO* and refined in SEPV), the predicted $\Delta\mathbf{V}$ statistics, and design and reconstructed $\Delta\mathbf{V}$s for each encounter. The reference trajectory deterministic $\Delta\mathbf{V}$ only includes the trajectory-shaping maneuvers, whereas the reconstructed $\Delta\mathbf{V}$ incorporates the deterministic and statistical parts of all maneuvers. The predicted $\Delta\mathbf{V}$ mean, 1-σ, and 95%† values were computed via LAMBIC ‡. These $\Delta\mathbf{V}$ predictions account for statistical variations in both maneuver execution errors and OD. The average navigation $\Delta\mathbf{V}$ cost per encounter for the first year of the Equinox Mission was about 0.6 m/s (variance = 1.9 m/s)§, compared to the 0.3 m/s average $\Delta\mathbf{V}$ cost of the prime mission (variance = 0.4 m/s). Any negative value $\Delta\mathbf{V}$ cost denotes propellant savings due to maneuver cancellations and/or biasing.

Table 3. Maneuver Performance per Encounter *Titan-44 to Titan-58*

Encounter Span	Ref. Traj. Det. $\Delta\mathbf{V}$ (m/s)	Predicted $\Delta\mathbf{V}$ Statistics Mean (m/s)	1-σ (m/s)	95% (m/s)	Design $\Delta\mathbf{V}$ (m/s)	Recon. $\Delta\mathbf{V}$ (m/s)	Navigation $\Delta\mathbf{V}$ Cost* (m/s)
T44-T45	11.960	12.802	0.596	14.007	12.358	12.349	0.389
T45-E4	2.667	2.959	0.448	3.702	2.541	2.539	-0.128
E4-E5	18.154	19.113	1.324	22.026	18.373	18.349	0.195
E5-E6/T46	10.263	10.635	0.253	11.115	10.565	10.550	0.286
T46-T47	8.533	9.747	1.124	11.852	14.256	14.247	5.714
T47-T48	0.838	1.898	0.927	3.721	0.855	0.847	0.009
T48-T49	3.091	4.925	0.996	6.720	4.692	4.680	1.589
T49-T50	4.762	5.593	0.668	6.898	4.673	4.670	-0.092
T50-T51	5.066	5.835	0.576	7.054	5.417	5.408	0.342
T51-T52	0.016	1.304	0.833	2.937	0.753	0.748	0.732
T52-T53	7.001	7.244	0.275	7.803	7.128	7.124	0.123
T53-T54	2.271	2.346	0.056	2.457	2.491	2.486	0.215
T54-T55	2.253	2.408	0.143	2.711	2.276	2.267	0.014
T55-T56	1.146	1.407	0.305	2.076	1.469	1.463	0.318
T56-T57	2.013	2.123	0.159	2.452	2.176	2.170	0.157
T57-T58	2.453	2.584	0.156	2.891	2.441	2.441	-0.012

* Navigation $\Delta\mathbf{V}$ cost = total reconstructed $\Delta\mathbf{V}$ - total reference trajectory deterministic $\Delta\mathbf{V}$ (per encounter).

The design characteristics for OTM-159 to OTM-205 are summarized in Table 4, grouped and separated by targeted encounters. The true anomaly listed is for an osculating ellipse with respect to Saturn and indicates where the spacecraft was in the orbit at the time of the maneuver or encounter (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 it counts multiple revolutions. Each $\Delta\mathbf{V}$ value listed is the total $\Delta\mathbf{V}$ from the sum of the burn, turns, including the pointing-bias-fix turn for MEA, and $\Delta\mathbf{V}$s due to deadband tightening for RCS burns. The design $\Delta\mathbf{V}$s, computed using DPTRAJ,[21] were commanded to the spacecraft. The reconstructed $\Delta\mathbf{V}$s were determined by the OD trajectory smoothing after the OTMs were performed.

*CATO (Computer Algorithm for Trajectory Optimization) is a medium-precision trajectory optimization program.
†95% $\Delta\mathbf{V}$ means that the maneuver $\Delta\mathbf{V}$ size will be less than or equal to this value with a 95% probability.
‡Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC), see Ref. 20.
§$\Delta\mathbf{V}$ cost to the E6/T46 double flyby was counted twice for each flyby.

Table 4. Maneuver History

Maneuver	Orbit Location	Maneuver Time (UTC/SCET)	True Anom. (deg)	Central Angle (deg)	Total Design ΔV Mag. (m/s)	Total Design ΔV RA (deg)	Total Design ΔV DEC (deg)	Roll Turn (deg)	Yaw Turn (deg)	Burn Time (sec)	Total Reconstructed ΔV Mag. (m/s)	Total Reconstructed ΔV RA (deg)	Total Reconstructed ΔV DEC (deg)	Burn Type
OTM-159	*T44∼per*	*23-Jun-2008 06:24:00*	*-45.39*	*2014.64*	*12.185*	*32.83*	*64.36*	*88.14*	*-84.74*	*73.77*	*12.179*	*32.71*	*64.33*	*MEA*
OTM-160	T45-3d	27-Jul-2008 14:36:00	-141.12	310.77	0.173	239.51	-66.89	-22.81	-84.24	142.37	0.169	239.11	-66.88	RCS
Titan-45 (T45)		*31-Jul-2008 02:14:16 ET*	*168.61*		*B · R = 3246.4 km*		*B · T = -3029.2 km*		*Alt. = 1613 km*			*Outbound*		*11.8 days to E4*
OTM-162	T45+4d	03-Aug-2008 22:15:00	-109.34	460.18	2.541	336.10	44.33	90.42	-52.00	15.48	2.539	336.02	44.16	MEA
OTM-163	E4-3d	08-Aug-2008 21:20:00	-171.20	162.13					*CANCELLED*					
Enceladus-4 (E4)		*11-Aug-2008 21:07:24 ET*	*-9.05*		*B · R = 73.4 km*		*B · T = 291.7 km*		*Alt. = 54 km*			*Outbound*		*58.9 days to E5*
OTM-164	E4+11d	23-Aug-2008 02:49:00	-177.80	2328.76	13.528	83.54	68.21	174.03	-100.30	81.57	13.518	83.28	68.25	MEA
OTM-164a	E4+40d	20-Sep-2008 18:49:00	171.62	899.65	0.893	62.61	52.30	64.73	-86.04	5.51	0.881	62.20	52.22	MEA
OTM-165	E4∼per	02-Oct-2008 10:19:00	-15.91	367.60	3.937	104.79	66.91	-54.27	-105.05	23.71	3.935	104.64	66.94	MEA
OTM-166	E5-3d	06-Oct-2008 18:05:00	-172.09	163.51	0.015	186.73	2.35	42.65	-160.36	8.95	0.015	186.61	2.34	RCS
Enceladus-5 (E5)		*09-Oct-2008 19:07:45 ET*	*-8.54*		*B · R = 68.2 km*		*B · T = 267.3 km*		*Alt. = 28 km*			*Outbound*		*21.9 days to E6*
OTM-167	E5+3d	12-Oct-2008 23:51:00	173.54	1077.52	3.340	228.56	-72.34	58.65	-89.55	20.18	3.337	228.90	-72.46	MEA
OTM-168	E5∼per	17-Oct-2008 09:10:00	65.14	826.09	6.993	127.20	40.34	-46.50	-127.73	41.88	6.988	127.15	40.36	MEA
OTM-169	T46-5d	29-Oct-2008 16:37:00	-156.88	328.14	0.232	168.19	-46.02	83.47	-127.65	193.82	0.225	168.05	-45.93	RCS
Enceladus-6 (E6)		*31-Oct-2008 17:15:56.6 ET*	*-8.31*		*B · R = 77.2 km*		*B · T = 415.7 km*		*Alt. = 176 km*			*Outbound*		*3.0 days to E6*
Titan-46 (T46)		*03-Nov-2008 17:36:28 ET*	*165.73*		*B · R = 1320.0 km*		*B · T = 3698.5 km*		*Alt. = 1100 km*			*Outbound*		*15.9 days to T47*
OTM-170	T46∼per	08-Nov-2008 22:23:00	-1.79	525.91	9.100	207.73	-61.14	127.47	-104.62	54.64	9.097	207.85	-61.21	MEA
OTM-171	T46∼apo	12-Nov-2008 22:09:00	179.88	344.05	5.155	337.73	28.51	-25.85	-33.84	30.89	5.149	337.78	28.51	MEA
OTM-172	T47-3d	16-Nov-2008 08:09:00	-104.04	267.98					*CANCELLED*					
Titan-47 (T47)		*19-Nov-2008 15:57:33 ET*	*163.72*		*B · R = 1533.1 km*		*B · T = -3531.7 km*		*Alt. = 1023 km*			*Outbound*		*15.9 days to T48*
OTM-173	T47+4d	23-Nov-2008 21:25:00	-84.16	612.92	0.787	331.25	18.23	33.68	-28.50	4.83	0.779	331.47	18.16	MEA
OTM-174	T47∼apo	27-Nov-2008 21:10:00	172.53	356.28					*CANCELLED*					
OTM-175	T48-4d	01-Dec-2008 20:56:00	-83.05	251.92	0.068	301.93	-34.72	-94.62	-54.88	57.03	0.068	301.73	-34.95	RCS
Titan-48 (T48)		*05-Dec-2008 14:26:50 ET*	*171.38*		*B · R = 86.2 km*		*B · T = -3786.6 km*		*Alt. = 960 km*			*Outbound*		*15.9 days to T49*
OTM-176	T48+4d	09-Dec-2008 20:27:00	17.52	519.91	3.038	108.69	54.63	-34.62	-106.75	18.30	3.034	108.39	54.68	MEA
OTM-177	T48∼apo	13-Dec-2008 20:13:00	-178.40	355.73	1.627	36.72	58.10	-120.47	-69.95	9.87	1.620	36.26	58.00	MEA
OTM-178	T49-4d	17-Dec-2008 19:58:00	19.05	158.37	0.026	148.84	-10.39	48.18	-151.38	20.17	0.026	148.88	-10.29	RCS
Titan-49 (T49)		*21-Dec-2008 13:00:57 ET*	*178.67*		*B · R = 2737.6 km*		*B · T = -2631.6 km*		*Alt. = 970 km*			*Outbound*		*47.8 days to T50*
OTM-179	T49+3d	24-Dec-2008 19:44:00	-94.72	1716.58					*CANCELLED*					
OTM-180	T49∼per	24-Jan-2009 03:48:00	18.97	523.11	4.673	95.92	52.75	-31.11	-99.91	27.73	4.670	95.88	52.70	MEA
OTM-181	T50-3d	04-Feb-2009 10:34:00	115.99	66.26					*CANCELLED*					
Titan-50 (T50)		*07-Feb-2009 08:51:57 ET*	*174.90*		*B · R = 3778.5 km*		*B · T = -253.6 km*		*Alt. = 960 km*			*Outbound*		*47.8 days to T51*
OTM-182	T50+3d	10-Feb-2009 10:04:00	-128.63	1372.89	0.370	93.69	2.15	-175.99	-100.09	2.29	0.364	93.33	1.51	MEA
OTM-183	T50∼per	09-Mar-2009 08:20:00	-27.44	551.99	5.026	219.84	-45.96	156.88	-108.76	29.86	5.023	220.06	-45.98	MEA
OTM-183x	T51-9d	18-Mar-2009 00:05:00	-135.25	299.95	0.020	129.63	19.70	90.87	-139.42	14.15	0.022	129.76	19.63	RCS
OTM-184	T51-3d	24-Mar-2009 07:20:00	92.93	72.00					*CANCELLED*					
Titan-51 (T51)		*27-Mar-2009 04:44:42 ET*	*98.22*		*B · R = 1621.7 km*		*B · T = -3422.7 km*		*Alt. = 960 km*			*Outbound*		*7.9 days to T52*
OTM-186	T51∼per	29-Mar-2009 13:05:00	32.15	123.90	0.753	138.34	14.05	177.34	-147.70	4.62	0.748	138.18	13.91	MEA
OTM-186a	T52-3d	01-Apr-2009 06:35:00	95.32	60.81					*CONTINGENCY*					
Titan-52 (T52)		*04-Apr-2009 01:48:53 ET*	*-67.85*		*B · R = 6416.7 km*		*B · T = -2827.3 km*		*Alt. = 4150 km*			*Inbound*		*15.9 days to T53*
OTM-188	T52+3d	07-Apr-2009 06:19:00	-45.21	286.03					*CANCELLED*					
OTM-189	T52∼per	12-Apr-2009 12:04:00	89.92	152.93	7.128	103.23	49.13	14.52	-109.94	42.18	7.124	103.09	49.12	MEA
OTM-190	T53-3d	17-Apr-2009 05:33:00	-174.74	55.81					*CANCELLED*					
Titan-53 (T53)		*20-Apr-2009 00:21:51 ET*	*-89.48*		*B · R = 6194.0 km*		*B · T = -1837.9 km*		*Alt. = 3600 km*			*Inbound*		*15.9 days to T54*
OTM-191	T53∼per	23-Apr-2009 05:03:00	-28.01	277.46					*CANCELLED*					
OTM-192	T53∼apo	28-Apr-2009 11:02:00	116.53	133.37	2.491	124.71	27.84	163.45	-133.16	14.88	2.486	124.57	27.87	MEA
OTM-193	T54-3d	02-May-2009 21:02:00	-166.66	56.21					*CANCELLED*					
Titan-54 (T54)		*05-May-2009 22:55:21 ET*	*-97.37*		*B · R = 6010.0 km*		*B · T = -1071.5 km*		*Alt. = 3245 km*			*Inbound*		*15.9 days to T55*
OTM-194	T54∼per	09-May-2009 04:01:00	-17.41	265.76					*CANCELLED*					
OTM-195	T54∼apo	14-May-2009 10:00:00	133.04	115.43	2.229	287.36	-33.29	-35.44	-57.57	13.32	2.222	287.54	-33.27	MEA
OTM-196	T55-3d	18-May-2009 19:45:00	-162.54	51.09	0.047	269.18	-44.81	-77.37	-75.57	36.94	0.044	268.60	-44.66	RCS
Titan-55 (T55)		*21-May-2009 21:27:47 ET*	*-101.52*		*B · R = 3811.4 km*		*B · T = -266.3 km*		*Alt. = 965 km*			*Inbound*		*15.9 days to T56*
OTM-197	T55∼per	25-May-2009 02:59:00	3.72	238.88					*CANCELLED*					
OTM-198	T55∼apo	30-May-2009 08:58:00	150.26	92.27	1.469	330.53	16.24	45.94	-26.21	8.83	1.463	330.54	16.20	MEA
OTM-199	T56-3d	03-Jun-2009 18:42:00	-161.09	43.62					*CANCELLED*					
Titan-56 (T56)		*06-Jun-2009 20:01:06 ET*	*-113.27*		*B · R = 3818.7 km*		*B · T = 123.3 km*		*Alt. = 965 km*			*Inbound*		*15.9 days to T57*
OTM-200	T56+3d	10-Jun-2009 08:12:00	55.91	179.46	2.146	263.48	-58.85	-20.65	-77.70	12.81	2.140	263.63	-58.84	MEA
OTM-201	T56∼apo	15-Jun-2009 01:26:00	158.20	77.15	0.030	239.14	-49.33	-82.28	-95.79	22.33	0.030	238.72	-49.12	RCS
OTM-202	T57-3d	19-Jun-2009 17:40:00	-161.77	37.10					*CANCELLED*					
Titan-57 (T57)		*22-Jun-2009 18:33:41 ET*	*-123.50*		*B · R = 3785.4 km*		*B · T = 439.5 km*		*Alt. = 955 km*			*Inbound*		*15.9 days to T58*
OTM-203	T57+4d	26-Jun-2009 07:09:00	94.61	133.31	2.425	273.08	-30.52	67.75	-70.80	14.43	2.425	273.24	-30.46	MEA
OTM-204	T57∼apo	01-Jul-2009 00:24:00	165.43	62.52	0.016	235.13	-43.89	-88.21	-101.14	10.05	0.016	234.90	-43.83	RCS
OTM-205	T58-3d	05-Jul-2009 16:38:00	-163.33	31.28					*CANCELLED*					
Titan-58 (T58)		*08-Jul-2009 17:05:09 ET*	*-132.83*		*B · R = 3752.0 km*		*B · T = 722.8 km*		*Alt. = 965 km*			*Inbound*		*15.9 days to T59*

Twenty-nine of the forty-five planned maneuvers were performed. Twenty-two maneuvers were implemented with the MEA while nine maneuvers used the RCS. Performing the majority of these maneuvers with the MEA was advantageous because it allowed RCS hydrazine savings.

When a maneuver design produces a very small $\Delta\mathbf{V}$, analysis for cancellation is conducted.[22,23] Tables 4 and 5 note the OTMs that were cancelled in this year of operations. Most OTMs were cancelled primarily on the basis of acceptable downstream $\Delta\mathbf{V}$ costs. The mean cancellation cost for the first year of the Equinox Mission was about -0.2 m/s (variance = 0.4 m/s). Cancellation also reduces spacecraft use and ground-system stress. Cancellation takes place only after considering several factors: maneuver magnitude, whether the resulting trajectory deviations are acceptable, deviations in the next target's B-plane asymptote, pointing requirements for science observations, effects on downstream maneuvers, and $\Delta\mathbf{V}$ penalty.

Table 5. Maneuver Cancellation Summary *OTM-160 to OTM-205*

Maneuver	Description	Location	Magnitude (m/s)	Cancellation Cost (m/s)
OTM-163	approach	E4-3d	0.048	-0.0365
OTM-172	approach	T47-3d	0.017	-0.2984
OTM-174	shaping	T47 apo	0.276	-2.0793
OTM-179	cleanup	T49+3d	0.050	0.4577
OTM-181	approach	T50-3d	0.042	-1.1906
OTM-184	approach	T51-3d	0.011	0.2792
OTM-186a	contingency	T52-3d	0.017	-0.2655
OTM-188	cleanup	T52+3d	0.063	0.0214
OTM-190	approach	T53-3d	0.015	-0.0150
OTM-191	cleanup	T53 per	0.028	-0.0084
OTM-193	approach	T54-3d	0.016	-0.1081
OTM-194	cleanup	T54 per	0.006	-0.0032
OTM-197	cleanup	T55 per	0.133	0.1547
OTM-199	approach	T56-3d	0.015	-0.0083
OTM-202	approach	T57-3d	0.015	0.0940
OTM-205	approach	T58-3d	0.018	-0.0013

* All cancelled maneuvers were designed for the RCS.

For very small maneuvers where there is a need to meet flyby accuracy requirements for science observations, a shift in the TCA of the targeted encounter body is considered for implementation. Specifically, if the $\Delta\mathbf{V}$ is smaller than the prescribed operational guideline for RCS maneuvers (9 mm/s) a change in the target time to increase the maneuver magnitude is examined. Target time is adjusted, rather than the B-plane targets because it imposes the minimum downstream $\Delta\mathbf{V}$ cost. The required time of adjustment is estimated by a linear model of the maneuver, $\Delta V = \mathbf{K}^{-1}\Delta B$. With $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ fixed, the $\Delta\mathbf{V}$ magnitude becomes a quadratic equation in terms of time-of-flight[7] and the smaller of the two solutions for $\Delta\mathbf{V}$ was generally chosen for analysis.

MANEUVER OPERATIONS YEAR IN REVIEW

Titan-45 (T45)

The first maneuver of the Equinox Mission, OTM-160, was the approach maneuver to T45. The majority of the encounter targeting had been accomplished with the final maneuver of the prime mission, OTM-159, which was a 12.18 m/s MEA burn. The maneuver design was uploaded and executed on the spacecraft nominally. During OTM monitoring, the Navigation Team saw lower $\Delta\mathbf{V}$ delivered for this maneuver than predicted. The OTM-160 magnitude error was 3-σ in the underburn direction, with 0.6-σ accounted for by a lower than average $\Delta\mathbf{V}$ from deadbanding* following the termination of the burn. This left a "burn-only error" of 2.4-σ, which indicated that thruster performance had degraded between recent RCS burns (OTM-150 and OTM-156), and prompted continued scrutiny of thruster performance.

Enceladus Close Flybys

The prime mission discovery of water plumes emanating from Enceladus' south pole motivated the Equinox Mission reference trajectory to include closer flybys of Enceladus[24] allowing the spacecraft to fly through the debris plumes in an effort to better analyze the plume material and its source. As a result, seven of 33 flybys during the Equinox Mission are dedicated to the icy moon Enceladus (E4 through E10). Two of the seven flybys are less than 50 km at closest approach (E4 and E5), and both were accomplished during the first year of the Equinox Mission.

These low-altitude flybys offered a new challenge for the Navigation Team. In addition to standard operations analysis, maneuver analyses were conducted to prepare for the upcoming Enceladus flybys during the first year of the Cassini Equinox Mission.[25] These analyses included: (1) possible fault scenarios that may result in undesirable encounter conditions,[26] (2) contingency maneuver designs in response to faults†, (3) cancellation studies (downstream $\Delta\mathbf{V}$penalties), and (4) flyby altitude verifications (for nominal or lower flyby altitudes). Table 6 lists the supplemental maneuver analysis for the E4-E6 flybys. A description of OD analysis performed for E4-E6 was previously published by the Cassini Navigation Team.[27]

Table 6. Equinox Mission Enceladus Flybys June 2008 - July 2009

Flyby	Date	Altitude	Associated OTMs	Supplemental Maneuver Analysis
E4	11-Aug-2008	50.0 km	162, 163	Contingency (leaking thruster); cancellation of OTM-163
E5	09-Oct-2008	25.0 km	164, 164a, 165, 166	Contingency (leaking thruster)
E6	31-Oct-2008	200.0 km	167, 168, 169	Contingency; Non-targeted double flyby; 168-BU Cost Reduction

T45 to E4 Transfer

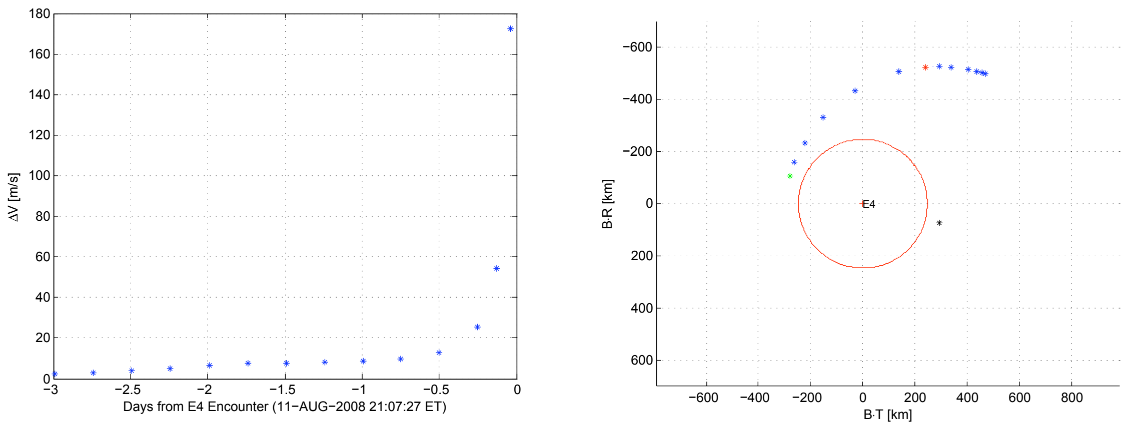
The only deterministic maneuver targeting Cassini's fourth encounter with Enceladus was OTM-162. This maneuver was vital to setting up the E4, E5, and E6 encounters. Contingency studies were conducted prior to this flyby to address concerns about thruster leaks after this maneuver that could cause the spacecraft to be on an Enceladus impacting trajectory as well as cancellation considerations for OTM-163. Ultimately, the E4 flyby confirmed that cracks in the moon's surface were the source of jets spewing water vapor into space and the primary source of Saturn's E-ring.[?] The flyby also confirmed a 16-km correction in the downtrack position of the moon that was predicted in the months prior to that encounter.[27]

*Deadbanding is thrusting required to maintain attitude control before returning to RWA control.

†A leaking thruster while under RCS control can occur during a maneuver, adding unexpected $\Delta\mathbf{V}$ and usually leaving the spacecraft in a safing mode.

E4 Contingency Maneuver Studies

On August 11, 2008, the Enceladus-4 (E4) encounter incorporated a 50-km flyby. As a result of the close flyby, contingency maneuvers were considered for the cases that the spacecraft would be on an impacting trajectory with Enceladus days before the encounter. One study included a "fly-across disk" emergency maneuver design that would guarantee the spacecraft was not on an impacting trajectory. Figure 6a shows that the $\Delta\mathbf{V}$ cost for such an emergency maneuver would have been 8.5 m/s or less, depending on the time of the maneuver. Figure 6b shows the locations where the emergency maneuver could have taken the spacecraft.



(a) $\Delta\mathbf{V}$ cost of a maneuver that would take Cassini across the E4 tumbling disk.

(b) Final spacecraft position if E4 recovery maneuver were performed.

Figure 6. E4 Fly-Across Disk Contingency Maneuver

E4 Leaking Thruster Contingency Studies

There has been no history of any leaking thrusters with the spacecraft, but the scenario is theoretically possible. The spacecraft office (SCO) and Navigation teams conducted analysis on whether a leaking thruster during the Enceladus approach could adversely affect the location of the spacecraft. E4 studies revealed worse case scenarios in which a leaking thruster could move the spacecraft on an Enceladus impacting trajectory.[26]

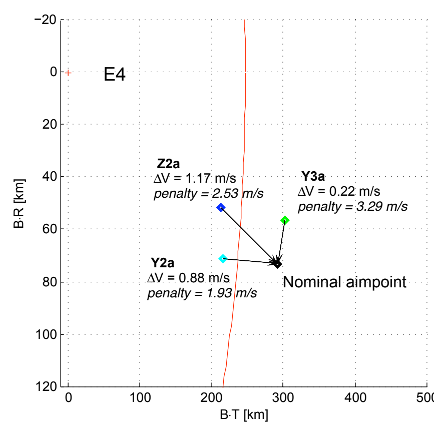
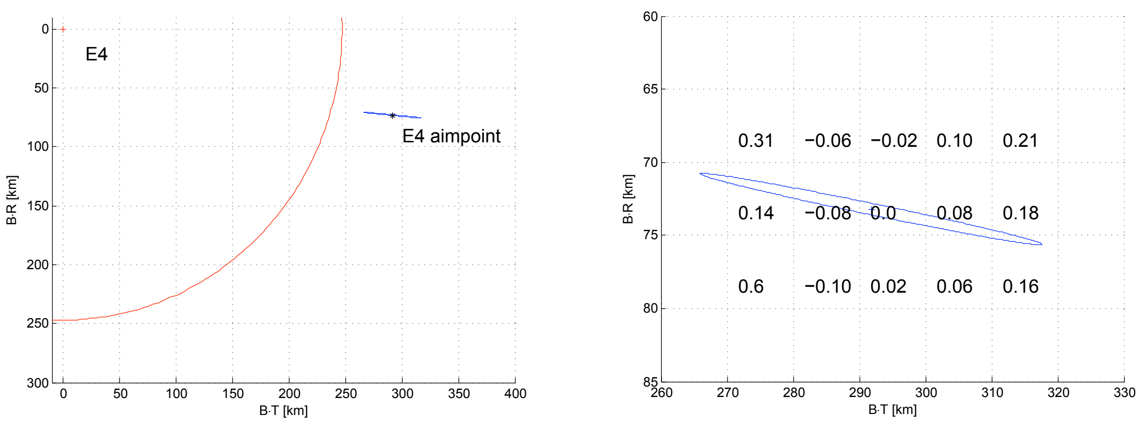


Figure 7. E4 Leaking Thruster Study.

Therefore, the Cassini project developed a contingency plan that included a recovery maneuver design to return the spacecraft to a nominal aimpoint. This maneuver would have taken place one day before the Enceladus encounter (OTM-163x). For robustness, maneuver designs were also made to return the spacecraft 20 km (B-plane magnitude) from the nominal aimpoint. Figure 7 presents the results for this study. The locations of the three worst leaking thruster cases with respect to the E4 disk are given. The $\Delta\mathbf{V}$ cost for a maneuver (OTM-163x) performed one day before the flyby is shown, along with the respective downstream $\Delta\mathbf{V}$ penalty. The $\Delta\mathbf{V}$ cost of performing a recovery maneuver (OTM-163x) to move away from an impacting trajectory, ranged between 0.88 m/s to 1.17 m/s, with the downstream penalty ranging from 1.93 m/s to 2.53 m/s.

To reduce the possibility of a leaking thruster during the approach maneuver, cancellation of the E4 approach maneuver was considered. Figure 8 illustrates the approximate downstream $\Delta\mathbf{V}$ cost of OTM-163 cancellation, based on the spacecraft location after the execution of OTM-162. The cancellation analysis revealed small acceptable $\Delta\mathbf{V}$ penalties (36.5 mm/s). OTM-163 was cancelled after nominal execution of OTM-162 and determination that navigation statistical pointing uncertainties at E4 were far larger than the mean pointing error incurred by cancelling the maneuver (25 mrad vs. 8.5 mrad at closest approach). The potential improvement in accuracy was not justified compared to the risk of performing a maneuver that also increased trajectory uncertainties.



(a) Maneuver delivery (blue ellipse) with respect to E4 disk (red circle).

(b) Close-up view of E4 aimpoint and maneuver delivery. Values indicate the downstream $\Delta\mathbf{V}$ cost (m/s) if E4 approach maneuver is cancelled.

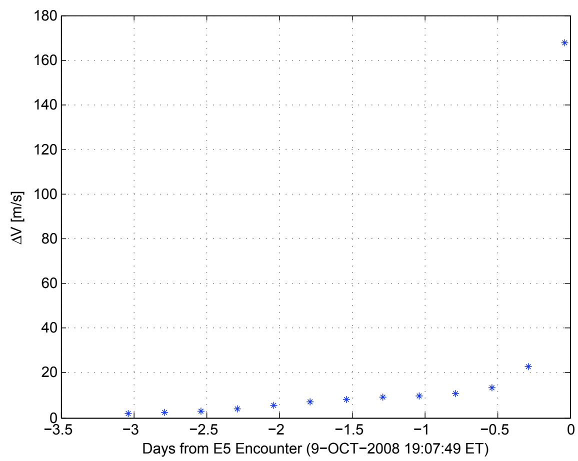
Figure 8. E4 Maneuver Cancellation Study. *Approximate downstream $\Delta\mathbf{V}$ cost if approach maneuver (OTM-163) is cancelled for a specified trajectory.*

E4 to E5 Transfer

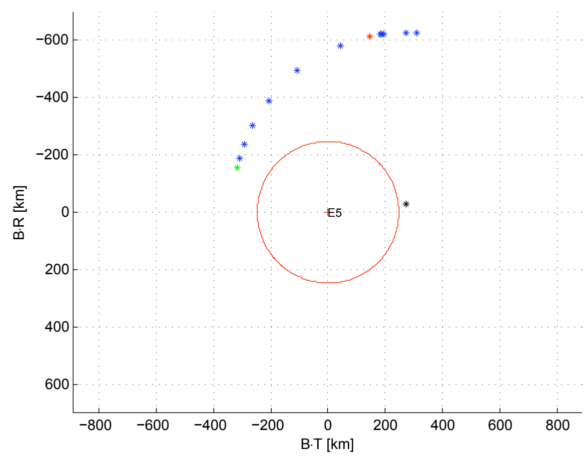
The transfer from E4 to E5 was the most expensive transfer of the Equinox Mission in terms of $\Delta\mathbf{V}$. The backup had a cost of about 4 m/s and redistributed the $\Delta\mathbf{V}$ across OTM-164, 164a and 165 in an undesirable way. The Navigation Team's goal was to stay as close to the reference trajectory for the E5 encounter as possible. The time-span between E4 and E5 was two months in duration, not enough time to allow the improved knowledge of the Enceladus orbit gained from the E4 flyby to deteriorate, this helped the orbit determination to converge well before the data cutoff. The large size of OTM-164 (greater than 13 m/s) made the post-maneuver trajectory errors insensitive to small OD errors. OTM-164 was near apoapsis and performed a large B-plane change as well as having an even larger time change component. OTM-164's design was approved early to allow for an early maneuver uplink, which decreases risk of ground system failures affecting maneuver execution. OTM-164a was the second deterministic maneuver of this segment which contained three deterministic maneuvers. It was named 164a to maintain the modulo 3 factor of determining the type of maneuver. OTM-165 was a large targeting maneuver to the E5 25-km flyby.

E5 Contingency Maneuver Studies

On October 9, 2008, the Enceladus-5 encounter incorporated a record low flyby of 25 km. This would be the closest flyby of an icy satellite of the mission. Similar analyses to those conducted for the E4 flyby were performed in advance of the E5 encounter. Figure 9a shows that the $\Delta\mathbf{V}$ cost for an emergency maneuver was 10 m/s or less if performed at least one day before the E5 flyby. Figure 9b shows the B-plane locations where an emergency maneuver could have taken the spacecraft.



(a) $\Delta\mathbf{V}$ cost of a maneuver that would take Cassini across the E5 tumbling disk starting from 2 days before encounter.



(b) Maneuver locations if E5 recovery maneuver were performed.

Figure 9. E5 Recovery Maneuver.

E5 Leaking Thruster Contingency Studies

As described in the E4 leaking thruster discussion, E5 studies revealed worse case scenarios in which a leaking thruster could move the spacecraft onto an Enceladus impacting trajectory.[26] This possibility warranted a contingency plan to return the spacecraft to a nominal aimpoint. Figure 10 presents the results for this study. The Figure shows the locations of the three worst leaking thruster cases with respect to the E5 disk (shown in red). The $\Delta\mathbf{V}$ cost for a recovery maneuver (OTM-166x) performed one day before the flyby is shown, along with the respective downstream $\Delta\mathbf{V}$ penalty. The $\Delta\mathbf{V}$ for performing OTM-166x ranged between 0.78 m/s to 1.36 m/s, with the downstream penalty ranging from 2 m/s to 2.5 m/s.

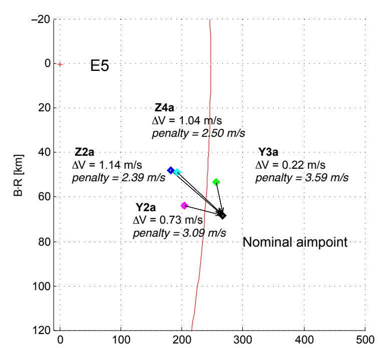


Figure 10. E5 Leaking Thruster Study.

OTM-166 Cancellation Analysis

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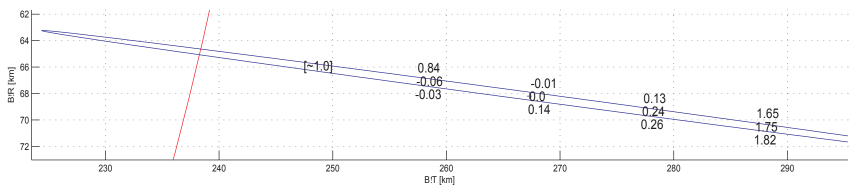

Figure 11. E5 Maneuver Cancellation Study.[26] *Approximate downstream ΔV cost of OTM-166 approach maneuver cancellation for a specified trajectory. E5 disk shown in red.*

E5 to E6/T46 Transfer

The Enceladus 6 (E6, altitude = 200 km) encounter on October 31, 2008 was part of the E6/T46 double flyby* with E6 non-targeted. The E6 flyby was made three days before an outbound flyby of Titan (T46, altitude = 1100 km) on November 3, 2008. Navigation implemented the nominal strategy of optimizing OTM-167 with OTM-168 targeted T46 since analysis showed a much lower ΔV cost when targeting to Titan rather than Enceladus 12. Due to the near singularity between OTM-168 and either E6 or T46, resulting in more than one possible maneuver design, special care was taken in the designs of OTM-167 and OTM-167-BU to ensure the optimal maneuver solution was selected.

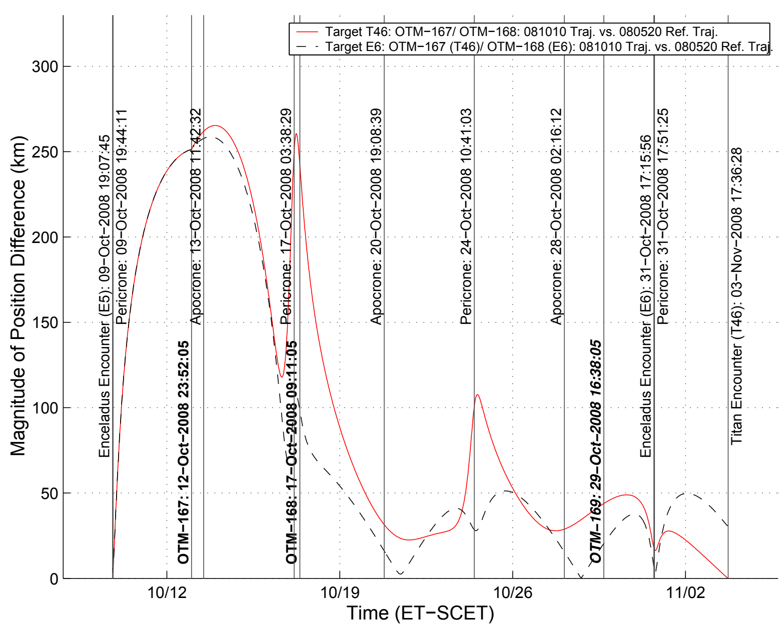

Figure 12. E5 to E6/T46 Trajectory Deviations

*A double flyby is a back-to-back flyby of Titan and another icy satellite with no OTMs between the encounters.

OTM-168 was a large, deterministic maneuver near pericrone. The nominal backup maneuver cost was identified as a concern for this maneuver and a number of other future maneuvers, therefore alternate backup maneuver strategies were analyzed.[28] Several experiments in Search, Path, Vary (SEPV)* were made with the design of OTM-168-BU[28] (Table 7). The nominal OTM-168-BU was scheduled only 5 hours after the prime maneuver time and preceded the double flyby (E6/T46). There were about two and a half 7-day revolutions before the T46 flyby. The goal of the backup studies was to preserve the sequence of encounters planned for the Equinox Mission, and to minimize $\Delta\mathbf{V}$ cost required to achieve the targeted flyby conditions in the reference trajectory. The specific requirement was to find a new backup maneuver time as well as new flyby conditions for the maneuver to target, which reduced the $\Delta\mathbf{V}$ cost after the flyby. The times shown in Table 7 were for existing tracking passes that were closest to the $\Delta\mathbf{V}$ optimal backup maneuver time.

Table 7. OTM-168 Backup Location Study using 081014 OD delivery

Scenario Description	Maneuver Time (ET)	Maneuver Size (m/s)	Downstream $\Delta\mathbf{V}$ Cost (m/s)	E6 Altitude (km)	T46 Altitude (km)
OTM-168	17-Oct-2008 09:11	6.99	0*	188	1100
6 hrs into DSS-14 track**	21-Oct-2008 17:06	38.43	37.36	38830	1450
6 hrs into DSS-55 track**	22-Oct-2008 09:36	24.58	21.39	33178	1399
New T46 w/No E6	22-Oct-2008 18:41	21.19	18.27	32429	1396

* 19.22 was the total $\Delta\mathbf{V}$ with a nominal OTM-168 up to OTM-177.
** The DSS-14 and DSS-25 options floated T46 to new values, returned to the reference trajectory at the nominal T47 flyby.

The OTM-169 maneuver produced a sizable B-plane change with the magnitude of the maneuver being fairly small. A very accurate delivery was desired because the $\Delta\mathbf{V}$ cost grew substantially with small differences to the B-plane encounter position. However, the OTM-169 RCS burn was executed with a substantial error that caused the encounter position to be off by approximately 10 km. This poor performance motivated close inspection of the RCS thruster performance. Based on their severe and rapid degradation found in the analysis of the performance the thruster branch was changed. The E5, E6, and T46 encounters required all 7 planned maneuvers with no cancellations.

T46 to T47 Transfer

As a consequence of the flyby error at T46, the size of OTM-170 increased. In addition to OTM-168-BU, OTM-170-BU was identified as a maneuver with a large penalty. Table 8 shows that for OTM-170 it was best to keep the planned backup location, but to change the aimpoint of the T47 flyby. OTM-171 increased in size substantially, from about 1.5-m/s to about 5-m/s due to the position difference of the T46 flyby, caused by the OTM-169 burn error. OTM-172 nominally would have required a magnitude of about 6 mm/sec, therefore a time bias of 0.3 sec would have been required to achieve an acceptable maneuver magnitude of about 12 mm/s. The comparison between this maneuver and the no-maneuver case indicated a downstream $\Delta\mathbf{V}$ savings of about 0.3 m/s with cancellation of OTM-172. Analysis by the science teams confirmed their pointing uncertainties were smaller with the no-burn scenario. Hence, OTM-172 was cancelled.

Table 8. OTM-170 Backup Location Study Using 081105 OD delivery

Scenario Description	Maneuver Time (ET)	Maneuver Size (m/s)	Downstream $\Delta\mathbf{V}$ Cost (m/s)	T47 Altitude (km)
OTM-170	08-Nov 2008 22:24	9.11	0*	1022.6
OTM-170-BU	09-Nov-2008 15:53	24.41	21.14	1022.6
OTM-170-BU/Float T47	09-Nov-2008 15:53	21.41	7.22	1000
OTM-171-BU/Float T47	13-Nov-2008 22:10	39.98	27.19	1445

* 24.40 was the total $\Delta\mathbf{V}$ with a nominal OTM-170 up to OTM-180.

*SEPV is a program that generates an integrated spacecraft state after searching on initial state or finite burn parameters

T47 to T48 Transfer

The targets for OTM-173 and OTM-174 were combined such that OTM-173 targeted directly to the desired encounter conditions. When the Navigation Team reviewed OTM-174, it was found that the OTM-173 execution errors could be cleaned up much more efficiently with OTM-175 ($\sim$80 mm/s) than with OTM-174 ($\sim$280 mm/s). $\Delta\mathbf{V}$ costs downstream of T48 were also much lower, with an expected savings of approximately 2.1 m/s by performing OTM-175 instead of OTM-174. As an added benefit to the $\Delta\mathbf{V}$ savings, the cancellation of OTM-174 meant that numerous team members would be able to enjoy Thanksgiving Day with their families.

T48 to T49 Transfer

OTM-176 was required to change the spacecraft trajectory off of a tumbling trajectory, due mainly to T46 flyby error. OTM-177 continued to compensate for the OTM-169 error. Navigation saw the effects of the flyby miss at T46 over three transfers; specifically a large effect was seen on the T46 to T47 and T48 to T49 transfers with almost no change to the T47 to T48 transfer, these costs are quantified in Table 3. OTM-178 was a small RCS statistical approach maneuver, however it was not a good candidate for cancellation because the OTM-177 MEA burn was an under-burn and the cost downstream of not reducing this error would have been 1.4 m/s.

T49 to T50 Transfer

OTM-179 was cancelled with a penalty of about 46 mm/s. Execution of the maneuver would have required a modified design to avoid a low rpm period on one of the reaction wheels. Cancellation of the maneuver at the prime location also eliminated the possibility of using the backup maneuver location on December 26 and the potential updating of the maneuver solution required on Christmas day. Since the OTM-180 backup maneuver carried a large $\Delta\mathbf{V}$ penalty, it was analyzed using a similar process to that used for the OTM-168-BU and OTM-170-BU. The results used for operations comparison are summarized in Table 9 below. The backup maneuver one week later which only changed one flyby was chosen as a better backup maneuver location then the nominal. This backup time was on an existing tracking pass and very close to a minimum $\Delta\mathbf{V}$ cost. Without OTM-181 the flyby at T50 was predicted to be about 9.3 km high. The OTM had a magnitude of about 40 mm/s, however cancellation would save about 1.2 m/s. The no OTM solution was provided to science and was found to be acceptable. The spacecraft operations office also recommended cancellation due to concerns related to the degrading A-branch RCS thrusters. Navigation recommended cancellation of OTM-181 and the project concurred.

Table 9. OTM-180 Backup Location Study Using 090104 OD delivery

Scenario Description	Maneuver Time (ET)	Maneuver Size (m/s)	Downstream $\Delta\mathbf{V}$ Cost (m/s)
OTM-180	24-Jan-2009 03:49	4.67	0
OTM-180-BU	25-Jan-2009 03:49	14.29	45.77
OTM-180-BU w/DSS-65 Float T50*	31-Jan-2009 03:18	12.89	6.4

* Alt. Δ 960 to 1003.87 km; B-plane $\angle$ Δ 59.92 to 61.51°; TCA Δ 7-Feb-2009 08:51:57 to 7-Feb-2009 08:52:10.3 ET

T50 to T51 Transfer

The T50-T51 transfer was unique because it set-up an eight day pi-transfer followed by nine consecutive 16-day transfers. The nominal strategy of performing an optimized OTM-182 chained with downstream maneuvers was implemented. An early estimate of OTM-182 yielded a $\Delta\mathbf{V}$ close to the 0.3 m/s boundary for choosing MEA or RCS. The use of MEA for OTM-182 over RCS was highly preferred due to the recent poor performance of RCS. In fact, the project planned to switch from the A to B-branch RCS thrusters due to this performance degradation before OTM-184. Options for inflating OTM-182 were considered but was not necessary; the post T50 maneuver solution was large enough to execute using the MEA (0.37 m/s). Although OTM-182 was small compared to OTM-183, combining it into the later would have incurred a large downstream $\Delta\mathbf{V}$ penalty nearly 4.8 m/s. OTM-182/OTM-183 is an excellent example of the potential benefit of distributing targeting over multiple maneuvers to reduce downstream $\Delta\mathbf{V}$ costs.

Of the four backup location studies encompassed in this year of operations, OTM-183 had the largest penalty for performing the backup as originally planned. Fortunately, many options for alternative maneuver times were available and changes to downstream flyby conditions were found acceptable that offered significant improvements to the standard backup maneuver. The maneuver that was selected to be the new backup is shown as the last option in Table 10. It was chosen because it allowed the most time in the event that a backup maneuver had to be used, and it spent the least amount of $\Delta\mathbf{V}$. Fortunately, OTM-183 was performed nominally. But the project chose to add a contingency maneuver, OTM-183x, prior to the approach maneuver, OTM-184, in order to test the RCS B-branch thrusters. Thanks, to the accurate execution of OTM-183x, OTM-184 was cancelled

Table 10. OTM-183 Backup Location Study Using 090115_101T50 OD delivery

Scenario Description	Maneuver Time (ET)	Maneuver Size (m/s)	Downstream $\Delta\mathbf{V}$ Cost (m/s)
OTM-183	09-Mar-2009 08:21	5.64	—
OTM-183-BU	10-Mar-2009 14:35	18.11	91.87
Nominal T51	TCA = 27-Mar-2009 04:44:42 ET, Altitude = 960 km		
Nominal T52	TCA = 04-Apr-2009 01:48:53 ET, Altitude = 4150 km		
OTM-183-BU	10-Mar-2009 14:35	14.04	20.92
Float T51	T51 (ΔTCA = -182.7 sec)		
OTM-183-BU	10-Mar-2009 14:35	13.95	18.35
Float T51 & T52	T51 (ΔTCA = -138.9 sec); T52 (ΔTCA = 20.1 sec, ΔAlt. = -157.4 km)		
OTM-183-BU	11-Mar-2009 08:35	7.52	12.55
w/ DSS-26, Float T51	T51 (ΔTCA = 4.4 sec)		
OTM-183-BU	11-Mar-2009 08:35	7.64	8.91
w/ DSS-26, Float T51 & T52	T51 (ΔTCA = 36.4 sec); T52 (ΔTCA = 67 sec, ΔAlt. = -107.32 km)		
OTM-183-BU	17-Mar-2009 08:05	18.14	12.82
w/ DSS-63, Float T51	T51 (ΔTCA = 9.2 sec, ΔAlt. = 73.36 km)		
OTM-183-BU	19-Mar-2009 07:35	12.08	6.76
w/ DSS-26, Float T51 Alt.	T51 (ΔTCA = 7.5 sec, ΔAlt. = 61.53 km)		

OTM-183x Contingency Maneuver

Since October 2008, the Cassini spacecraft operations team observed that the Cassini spacecraft A-Branch Z-facing thrusters (Z3A and Z4A) exhibited signs of degraded performance and recommended transition to the redundant RCS thruster B-Branch. The Cassini project decided to switch the thrusters during the week of March 11, 2009, days after the execution of OTM-183 (March 9, 2009) and before the next maneuver opportunity, OTM-184 (March 24, 2009). This hardware-driven activity initially posed no direct effect on spacecraft OTM activities. A careful review of the trajectory control events before and after the thruster swap revealed that OTM-184, the T51 approach maneuver, would have been the first planned maneuver to use the new thruster branch only days before a low altitude T51 flyby. Additionally, the OTM-183 MEA underburn placed the spacecraft trajectory within the Titan tumbling disk and guaranteed the need to take the first opportunity to perform a maneuver. Therefore, the trajectory control at T51, in conjunction with the first time use of the B-Branch thrusters, led to the decision to insert and execute OTM-183x. Since the insertion of a maneuver was a first time event for the Cassini tour it is not described in the navigation plan.[29]

T51 to T52 Transfer

This is the beginning of the equinox viewing orbits which will continue through T62. A constant line of apsides, -80°, occurs as a result of the eight-day pi-transfer, during which the spacecraft is transitioning the encounter longitude by 180°. OTM-186 increased in size from the navigation plan estimate, likely due to flyby miss at T46. OTM-186a was a contingency maneuver planned into the reference trajectory but was unneeded.

T52 to T53 Transfer

OTM-188 was cancelled since downstream $\Delta \mathbf{V}$ costs were determined to be relatively small, 21.4 mm/s from T52-T56, and science pointing requirements were satisfied as well. OTM-189 was executed extremely well as shown in Table 4. OTM-190 orientation was such that RWAs would have experienced unacceptable speed ranges; however, due to a combination of the excellent delivery from OTM-189 and a high altitude (3600 km) flyby, cancellation had no impact on either science pointing or downstream $\Delta \mathbf{V}$.

T53 to T54 Transfer

OTM-191 was cancelled thanks to an accurate high-altitude flyby on RWAs and a reasonably sized deterministic targeting maneuver; there was no $\Delta \mathbf{V}$ penalty, cancellation reduced spacecraft risk and life-cycles, and reduced staffing demands. OTM-192 was the first maneuver to implement the newest execution-error model. The project updated the execution-error model and Cassini's flight software on-board parameters that govern the main engine burn duration[12] at a highly desirable time; the OTM-192 preview contour showed that an underburn would have significant $\Delta \mathbf{V}$ costs downstream. OTM-192 was always planned as a MEA maneuver but grew a bit larger than statistical predictions. Cleaning up the T54 delivery after OTM-192 required a very small OTM-193 (less than 10 mm/s) implying that time biasing would be required if the OTM was to be executed. Further, cancelling the OTM reduced the downstream $\Delta \mathbf{V}$ estimates by about 0.1 m/s. As a final issue, both the prime and backup maneuvers required time biases to place the RWAs in an acceptable configuration during the OTMs. Science planning reviewed both the with and without OTM trajectories from the preliminary Navigation review and the pointing errors, without the OTM, was acceptable. Therefore, OTM-193 was cancelled.

T54 to T55 Transfer

OTM-194 was cancelled since the flyby of Titan did not perturb the trajectory by an amount large to need a correction. It was found that the minimum $\Delta \mathbf{V}$ solution did not require OTM-194. The smooth Titan flyby also resulted in a converged orbit determination solution after only one tracking pass. OTM-195 was executed nominally. OTM-196 was considered for cancellation but was chosen to be executed due to several factors such as the growth in magnitude of OTM-197, which is a periapsis burn, and the large asymptote errors obtained by cancellation.

T55 to T56 Transfer

OTM-183x was the first RCS maneuver executed on B-branch. This transfer began eight 16-day orbits; the first four orbits having large deterministic apoapsis maneuvers and the subsequent four orbits having large deterministic cleanup maneuvers. At the OTM-197 final cancellation review, the Navigation Team showed that the downstream cost of cancelling OTM-197 was about 155 mm/s. Accepting this relatively small cost reduced the Memorial Day holiday weekend workload and saved a maneuver cycle on the RCS thrusters. OTM-198 was the only maneuver executed to target the next encounter. The downstream cost of cancelling OTM-199 was not significantly different from the downstream cost if OTM-199 was executed. Therefore, the project decided to save a cycle on the RCS thrusters and OTM-199 was cancelled.

T56 to T57 Transfer

The targets for OTM-200 and OTM-201were combined after navigation analysis showed that this approach had little $\Delta\mathbf{V}$ cost in addition to increasing the likelihood of cancelling OTM-205, which was desirable from a ground systems perspective (July 5th maneuver). This approach allowed the team the flexibility to choose between cancelling either OTM-201 or OTM-202. It was also shown that the trajectory deviations were the same if OTM-200 and 201 were targeted in a chain or combined. Additionally, OTM-201 would become an RCS maneuver and it is desirable to limit throughput of hydrazine for RCS. In the course of OTM-200 analyses it was seen that OTM-200 had a close to 180° central angle, which may have been the cause of the navigation team seeing conjugate point solutions. The reduced cost of combining the two maneuvers as well as the spacecraft operations team report that RWA speeds were better for the combined case favored the single target solution. OTM-201 was preferred to function as the statistical approach maneuver for the T57 encounter, thereby enabling the cancellation of OTM-202 given an accurate OD for OTM-201 and an accurate execution of OTM-201. The delivery to T57 did not require further correction.

T57 to T58 Transfer

The Navigation Team found that the apoapsis maneuver could be combined with the cleanup maneuver (OTM-204 into OTM-203), much like the previous transfer. OTM-204 was designed to correct the execution error in OTM-203. Cancellation analysis showed that due to the large timing bias that would have been necessary to execute OTM-205, performing the maneuver would have caused a larger target miss at T58 than cancelling the maneuver.

CONCLUDING REMARKS

The Cassini-Huygens spacecraft has been navigated successfully through the first year of the Equinox Mission. The Equinox Mission had 45 maneuvers planned during this period. Twenty-nine maneuvers were performed in the prime locations, one of which was executed with a biased time-of-flight target. Sixteen maneuvers were cancelled. Twenty-one maneuvers were performed with the MEA, while nine utilized the RCS. Cassini achieved its lowest encounter on record, with a 25 km flyby of Enceladus. Additionally, a smooth transition was made of the RCS thruster branches, leading to the execution of the first contingency maneuver not included in the reference trajectory. Furthermore, the execution error model was updated to remove main engine magnitude biases, which was implemented through flight software patches. Supplemental analysis was conducted during operations to re-optimize backup locations, enabling valuable $\Delta\mathbf{V}$ cost savings. In conjunction with the operations excitement of the past year, studies and analysis for the future of the mission were rewardingly progressing. Cassini's outstanding performance is expected to continue and will facilitate stimulating science investigations of the Saturnian system in the final year of the Cassini Equinox Mission and beyond.

APPENDIX: B-PLANE DESCRIPTION

Planet or satellite targeting is described in aiming plane coordinates referred to as *B-plane* coordinates[17] (Fig. 13). The B-plane passes through the body center and perpendicular to the asymptote of the incoming trajectory (assuming 2 body conic motion). The vector $\mathbf{B}$ lies in the B-plane and extends from body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the body had no mass and did not deflect the flight path. Coordinates are defined along three orthogonal unit vectors, $\mathbf{S}$, $\mathbf{T}$, and $\mathbf{R}$ with the system origin at the body center. The $\mathbf{S}$ vector is parallel to the spacecraft V_∞vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). $\mathbf{T}$ is parallel to a convenient reference plane, and $\mathbf{R}$ completes an orthogonal triad with $\mathbf{S}$

and $\mathbf{T}$. The reference plane for $\mathbf{T}$ is generally the ecliptic plane (EMO2000). For Titan equator of date, the reference plane is in Titan's equatorial plane at the given epoch. With $\mathbf{S}$, $\mathbf{T}$, and $\mathbf{R}$ thus defined, a target point can be described in terms of the B-vector dotted into the $\mathbf{R}$ and $\mathbf{T}$ vectors ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$), or as the magnitude of $\mathbf{B}$ and the angle ϕ clockwise from $\mathbf{T}$ to $\mathbf{B}$ viewed along -$\mathbf{S}$.

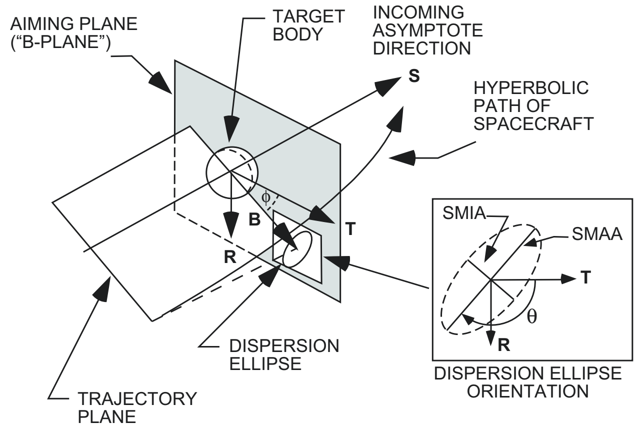

Figure 13. B-Plane Coordinate System.

Trajectory errors in the B-plane are often characterized by a one-σ dispersion ellipse, shown in Fig. 13. SMAA and SMIA denote the semimajor and semiminor axes of the ellipse; θ is the angle measured clockwise from the $\mathbf{T}$-axis to SMAA viewed along -$\mathbf{S}$.

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology. Copyright 2009 California Institute of Technology. Government sponsorship acknowledged.

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