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CASSINI SOLSTICE MISSION MANEUVER EXPERIENCE: YEAR THREE

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The Solstice Mission is the final extension of the Cassini spacecraft's tour of Saturn and its moons. To accommodate an end-of-mission in 2017, the maneuver decision process has been refined. For example, the Cassini Project now prioritizes saving propellant over minimizing maneuver cycles. This paper highlights 30 maneuvers planned from June 2012 through July 2013, targeted to nine Titan flybys and the final Rhea encounter in the mission. Of these maneuvers, 90% were performed to maintain the prescribed trajectory and preserve downstream ΔV. Recent operational changes to maneuver executions based on execution-error modeling and analysis are also discussed.

OVERVIEW

In July 2004, the Cassini spacecraft began a four-year tour of Saturn and its moons. Following the four-year Prime Mission, two subsequent extended missions were approved: a two-year Equinox Mission from September 2008 to September 2010, and a seven-year Solstice Mission starting in September 2010. The Solstice Mission is the final extension of Cassini's Saturn tour and is planned to conclude in September 2017. It increases the mission lifetime past Saturn's northern summer solstice in May 2017 in order to augment the temporal baseline observable to two Saturnian seasons.[1] To accommodate an end-of-mission in 2017, the maneuver decision process has been refined. For example, the Cassini Project now prioritizes preserving propellant over minimizing maneuver cycles. From June 2012 through July 2013, 90% of the planned maneuvers were performed by Cassini to closely maintain the prescribed trajectory. This maneuver approach yielded a propellant savings by minimizing the ΔV cost across several downstream maneuvers. In contrast, the propellant savings by canceling a maneuver may add ΔV to future maneuvers.

This paper focuses on the maneuver activities of the Cassini spacecraft from June 10, 2012 through July 23, 2013, which included 30 planned Orbit Trim Maneuvers (OTMs) and spanned the third year of the Solstice Mission. Earlier papers from the Cassini Maneuver Team reported on the OTMs during the four-year Prime Mission,[2,3,4,5] the two-year Equinox Mission,[6,7] and the first two years of the Solstice Mission.[8,9] The planned maneuvers in the third year of the Solstice Mission, OTM-326 through OTM-355, were used to achieve nine targeted flybys of Titan (T85–T93) and one encounter of Rhea (R4). These 10 encounters were part of the first half of the second inclined phase of the Solstice Mission. From July 2012 through April 2013, a series of short-period resonant Titan-to-Titan transfers (T85–T90), targeted by OTMs 326–346, increased the inclination from near zero to 61.7°. The majority of ring and high latitude Saturn atmospheric occultations in the Solstice Mission occurred during this phase, including the last planned targeted encounter of Rhea. From May 2013 through May 2014, a series of resonant and generally longer period orbits (most $>$ 32 days) reduces inclination from 61.7° to 40.7°. This phase was designed to provide both northern

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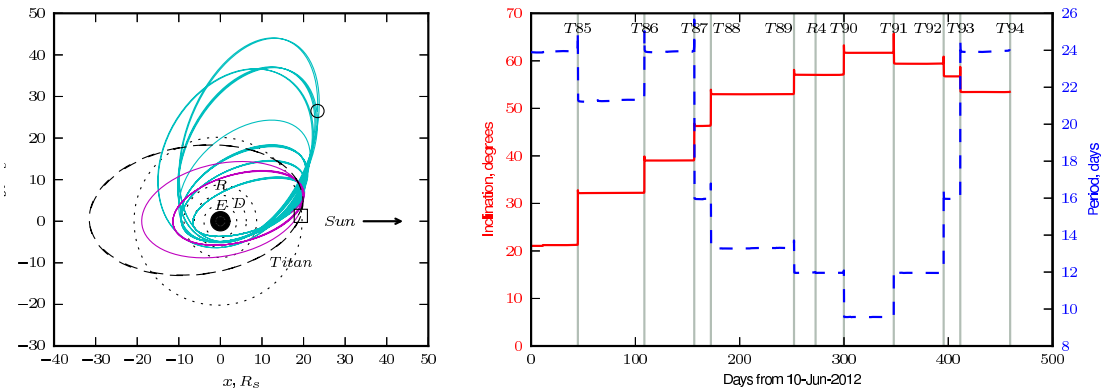
and southern hemisphere, low phase Titan surface coverage and multiple inclined passages through Saturn's magnetotail region.[1] The first three Titan flybys in this phase, T91–T93, were targeted by OTMs 347–355 and are discussed in this paper.



(a) Saturn North Polar View (Sun fixed)

(b) Inclination and Orbital Period

Figure 1. (Left) Cassini's trajectory from 10-Jun-2012 (circle) to 12-Sep-2013 (square) as viewed from Saturn's north pole, and outlining the orbits of Titan, Enceladus (E), Dione (D), and Rhea (R); Saturn and the rings are shown to scale, **In-2a** trajectory from 10-Jun-2012 to 23-May-2013 (cyan), **In-2b** trajectory from 23-May-2013 to 07-Aug-2013 (magenta); the Sun is to the right of the diagram; the unit distance Rs = 60,330 km: the equatorial radius of Saturn at 0.1 bar atmospheric pressure. (Right) the instantaneous orbital inclination with respect to Saturns true equator (solid line, left axis) and orbital period (dotted line; right axis). Encounters are labeled to highlight the effect of each flyby on the orbital parameters.

The petal and orbital elements plots presented in Figure 1 depict the spacecraft trajectory as viewed from Saturn's north pole, with the Sun direction along the horizontal axis, and the time profile of orbital inclination and orbital period, from which it is possible to determine the orbital effect of each flyby.

The execution-error models for Cassini's main engine and Reaction Control Subsystem (RCS) maneuvers were updated based on recent maneuver performance and first used in maneuver operations in August 2012.[10,11] In conjunction with these execution-error model updates, magnitude biases were removed either through a flight software change or within the maneuver design process. An analysis of the maneuver performance following these modeling changes in August 2012 will also be presented in this paper.

To address an end-of-mission date in 2017 and a dwindling fuel supply, the Cassini Project has modified its rationale for maneuver implementations and cancellations. In the early years of the mission, the reduction of maneuver cycles was a prime concern because propellant reserves were high. Now that Cassini is in its second extended mission, concerns have shifted towards fuel preservation. Reducing RCS maneuver cycles to help safeguard RCS functionality is still important. RCS is needed for attitude control, pointing Cassini's high-gain antenna to Earth for communication, and reaction wheel management. Several small main engine burns, as opposed to large RCS maneuvers, have been performed in the past year with hydrazine and RCS cycle preservation in mind. These small main engine maneuvers, which included the sole backup maneuver performed in this time period, OTM-353 BU, are discussed in this paper.

Figure 2 shows each maneuver and encounter in the scope of this paper as a function of true anomaly, with each row representing one spacecraft revolution around Saturn measured from apocrone to apocrone. Maneuvers are color-coded as either executed, cancelled, or planned in the future. This diagram provides the context of how each maneuver relates to the targeted encounters.[12] For example, on revolutions 167–169, OTMs 326–328 target Titan-85 (T85).

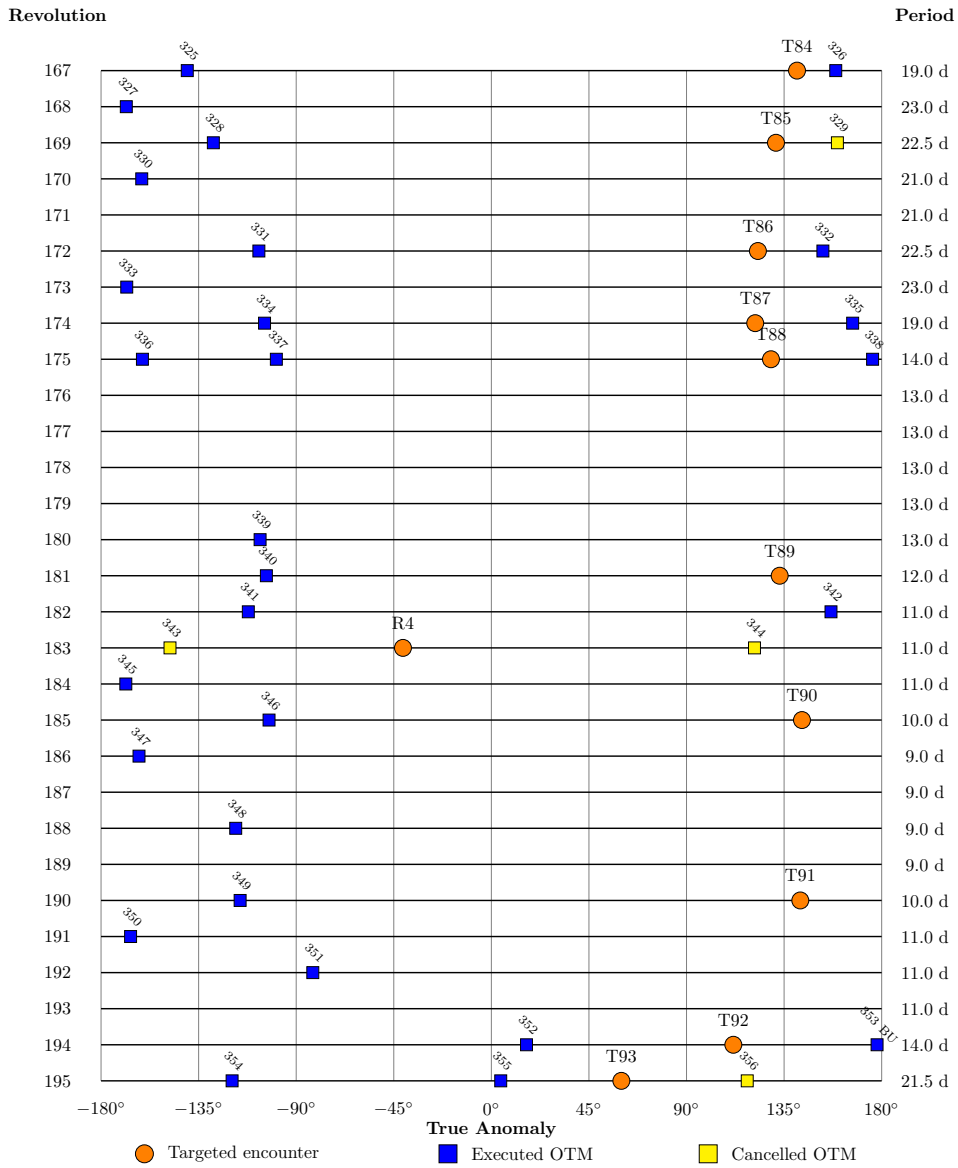


Figure 2. Titan-84 – Titan-93 Orbital Events. Each row corresponds to one revolution around Saturn; each revolution is numbered, and its anomalistic period is listed in days (time elapsed between two consecutive passes through apoapsis). One revolution spans 360 degrees of true anomaly (the horizontal axis), negative from apoapsis (180 deg) to periapsis (0 deg), and positive from periapsis to apoapsis.

NAVIGATION STRATEGY

The Cassini spacecraft takes advantage of the substantial gravity assists provided by each Titan encounter. For example, a Titan flyby at an altitude of 1,000 km and a V_∞ of 5.5 km/s supplies about 840 m/s of ΔV to Cassini; lower-altitude flybys impart even more. The maneuvers executed by Cassini are dwarfed in comparison: about 98% of the total ΔV required by the entire mission is provided by Titan alone.

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

to target the encounter conditions; and an approach maneuver, about three days before an encounter, is used to refine the orbit before an encounter, if necessary.

Maneuvers are performed by Cassini's bipropellant Main Engine Assembly (MEA) or monopropellant Reaction Control Subsystem (RCS) (see Figure 3). The RCS consists of four hydrazine thruster clusters grouped into two sets: the first one is along $\pm$YS/C, and is used to make balanced roll turns about the ZS/C axis; the second one faces the $-$ZS/C axis and is used to make unbalanced yaw turns about the YS/C axis. RCS is used for attitude control, reaction wheel momentum dumps, and small maneuvers (ΔV $<\sim$0.25 m/s). The MEA is used for larger maneuvers if the predicted burn time is at least 1.5 seconds, a minimum first set by OTM-318,[9] to avoid a software limitation of 1 second. Currently, this translates to MEA burns that are at least $\sim$0.25 m/s.

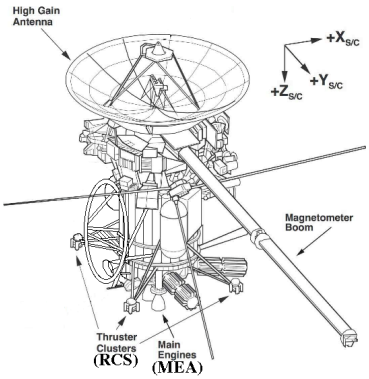


Figure 3. Cassini Orbiter

Typically the first two maneuvers are deterministic: their execution is usually required, and they are normally optimized together in a chained two-impulse optimization strategy, which minimizes total deterministic ΔV across several encounters while controlling asymptote errors without altering downstream flyby aimpoints after each encounter.[13] On the other hand, the approach maneuver is typically statistical: its execution depends on the accumulation of random error. The maneuvers are targeted to the upcoming encounters three B-plane[14] flyby conditions: the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$, and the time of flight. These targets were determined during the mission design phase, and are collectively known as the reference trajectory.

Each maneuver is executed in a turn-and-burn manner: the required burn attitude is achieved by performing a roll turn followed by a yaw turn (wind turns), the burn is then executed and, after completion, the turns are reversed to return to the original attitude (unwind turns). Turns performed with the Reaction Wheel Assembly (RWA) and roll turns performed by the RCS do not impart ΔV to the spacecraft. On the other hand, yaw turns executed by the RCS do impart ΔV because these thrusters are unbalanced about the YS/C axis. All roll turns and the yaw turn for RCS maneuvers are typically executed by the RWA. However, the yaw turn for MEA maneuvers is usually performed by RCS thrusters. For this reason, the computation of MEA maneuvers needs to account for the ΔV imparted by the turns.

Maneuver execution errors are modeled via the methodology proposed by Gates[15] which enables ΔV statistical analysis and the determination of the maneuver delivery accuracy.[16] The execution-error models for main engine and RCS maneuvers were updated in August 2012 based on recent maneuver performance and are discussed in a later section.

A planned maneuver can be canceled if it is determined that its execution will not improve encounter conditions, yield downstream ΔV savings, or if a subsequent maneuver can attain the encounter conditions at a lower ΔV cost. A common cancellation case is an approach maneuver preceded by accurate shaping maneuvers. These criteria are subordinate to science requirements. A more detailed account of the Project's maneuver cancellation process is provided in Reference 13.

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

Table 1. Maneuver History (OTMs 325–356)

Maneuver	Orbit Location	Maneuver Time (UTC SCET)	True Anomaly (deg)	Central Angle (deg)	Total Design $\Delta\mathbf{V}^*$ Mag. (m/s)	RA (deg)	Dec (deg)	Total Reconstructed $\Delta\mathbf{V}^*$ Mag. (m/s)	RA (deg)	Dec (deg)	Burn Type
OTM-325	T84−3d	03-Jun-2012 21:15	−140.22	287.89	0.038	155.62	−9.19	0.037	155.90	−9.36	RCS
Titan-84 (T84): 07-Jun-2012 00:08:27 ET SCET, Alt. = 959 km, Flyby ΔV = 858.8 m/s, Outbound, 47.8 days to T85											
OTM-326	T84+3d	10-Jun-2012 10:29	158.82	693.46	0.422	271.83	16.50	0.412	272.11	16.71	MEA
OTM-327	∼apo	21-Jun-2012 03:28	−168.39	660.69	10.119	262.33	−64.30	10.119	262.50	−64.32	MEA
OTM-328	T85−4d	21-Jul-2012 07:38	−128.20	260.42	0.172	175.05	−12.57	0.172	175.42	−12.81	RCS
Titan-85 (T85): 24-Jul-2012 20:04:14 ET SCET, Alt. = 1012 km, Flyby ΔV = 849.8 m/s, Outbound, 63.8 days to T86											
OTM-329	T85+3d	28-Jul-2012 07:08	159.58	1050.54	..... *CANCELLED*						
OTM-330	∼apo	07-Aug-2012 06:36	−161.26	1011.39	4.353	265.31	−32.02	4.357	265.53	−31.98	MEA
OTM-331	T86−3d	23-Sep-2012 13:47	−107.20	237.36	0.061	14.50	30.91	0.061	14.64	31.22	RCS
Titan-86 (T86): 26-Sep-2012 14:36:45 ET SCET, Alt. = 956 km, Flyby ΔV = 861.4 m/s, Outbound, 47.8 days to T87											
OTM-332	T86+4d	30-Sep-2012 03:16	152.89	685.28	0.190	328.26	17.79	0.190	327.98	18.02	RCS
OTM-333	∼apo	09-Oct-2012 13:01	−168.14	646.32	0.761	53.83	15.93	0.764	53.76	15.70	MEA
OTM-334	T87−4d	09-Nov-2012 18:46	−104.59	222.75	0.060	210.92	−4.90	0.060	210.57	−5.23	RCS
Titan-87 (T87): 13-Nov-2012 10:23:15 ET SCET, Alt. = 973 km, Flyby ΔV = 859.3 m/s, Outbound, 15.9 days to T88											
OTM-335	T87+4d	17-Nov-2012 00:31	166.62	324.04	0.255	207.93	−65.26	0.253	207.54	−65.89	MEA
OTM-336	∼apo	22-Nov-2012 00:16	−161.00	291.66	4.959	251.61	−14.18	4.961	251.57	−14.10	MEA
OTM-337	T88−3d	26-Nov-2012 00:01	−99.16	229.87	0.022	337.79	−45.43	0.021	337.56	−45.45	RCS
Titan-88 (T88): 29-Nov-2012 08:58:06 ET SCET, Alt. = 1014 km, Flyby ΔV = 850.1 m/s, Outbound, 79.7 days to T89											
OTM-338	T88+4d	02-Dec-2012 23:32	175.81	2118.92	0.028	227.95	−47.66	0.029	227.97	−47.52	RCS
OTM-339	∼apo	30-Jan-2013 20:09	−106.70	601.60	1.658	269.74	33.36	1.654	269.71	33.59	MEA
OTM-340	T89−4d	13-Feb-2013 05:26	−103.76	238.69	0.032	218.41	−30.47	0.031	218.51	−30.37	RCS
Titan-89 (T89): 17-Feb-2013 01:57:42 ET SCET, Alt. = 1978 km, Flyby ΔV = 681.4 m/s, Outbound, 20.7 days to R4											
OTM-341	T89+7d	24-Feb-2013 12:12	−112.12	431.33	1.450	257.50	36.47	1.447	257.46	36.59	MEA
OTM-342	R4−8d	02-Mar-2013 04:28	156.64	162.64	0.264	88.42	−72.62	0.261	86.66	−72.50	MEA
OTM-343	R4−3d	06-Mar-2013 17:58	−148.2	107.5	..... *CANCELLED*						
Rhea-4 (R4): 09-Mar-2013 18:18:34 ET SCET, Alt. = 1000 km, Flyby ΔV = 18.8 m/s, Inbound, 27.1 days to T90											
OTM-344	R4+3d	12-Mar-2013 03:44	121.35	737.66	..... *CANCELLED*						
OTM-345	∼apo	17-Mar-2013 03:30	−168.57	667.56	0.186	274.86	19.33	0.186	274.31	19.40	RCS
OTM-346	T90−4d	01-Apr-2013 16:16	−102.53	241.55	0.017	51.66	45.24	0.017	51.85	45.29	RCS
Titan-90 (T90): 05-Apr-2013 21:44:37.7 ET SCET, Alt. = 1400 km, Flyby ΔV = 773.3 m/s, Outbound, 47.8 days to T91, $\Delta\mathbf{TF}$= −0.3 sec											
OTM-347	T90+3d	09-Apr-2013 01:46	−162.5	1757.02	0.123	54.03	51.64	0.122	54.60	51.68	RCS
OTM-348	∼peri	30-Apr-2013 08:02	−117.9	992.45	0.495	249.16	11.49	0.495	249.42	11.67	MEA
OTM-349	T91−4d	19-May-2013 12:46	−115.87	270.47	0.017	44.1	59.22	0.017	44.44	59.26	RCS
Titan-91 (T91): 23-May-2013 17:34:01.8 ET SCET, Alt. = 970 km, Flyby ΔV = 857.8 m/s, Outbound, 47.8 days to T92, $\Delta\mathbf{TF}$= −0.2 sec											
OTM-350	T91+4d	27-May-2013 06:01	−166.38	1385.14	0.051	44.64	18.8	0.051	45.08	18.66	RCS
OTM-351	∼peri	11-Jun-2013 21:14	−82.33	941.21	0.820	109.47	−52.49	0.819	109.03	−52.72	MEA
OTM-352	T92−3d	07-Jul-2013 09:26	16.19	122.7	0.058	70.33	−42.55	0.058	70.35	−43.00	RCS
Titan-92 (T92): 10-Jul-2013 13:22:54 ET SCET, Alt. = 964 km, Flyby ΔV = 859.2 m/s, Outbound, 15.9 days to T93											
OTM-353	T92+4d	14-Jul-2013 02:40	163.5	298.0	..... *DELAYED*						
OTM-353 BU†	T92+5d	15-Jul-2013 02:40	177.9	283.7	0.253	43.60	20.89	*0.249*	*43.66*	*21.14*	MEA
OTM-354†	∼peri	19-Jul-2013 02:25	−119.4	221.0	2.265	107.29	−50.10	*2.269*	*106.74*	*−49.91*	MEA
OTM-355†	T93−3d	23-Jul-2013 08:24	4.3	97.2	0.072	280.57	50.18	*0.071*	*279.89*	*50.26*	RCS
Titan-93 (T93): 26-Jul-2013 11:57:29 ET SCET, Alt. = 1400 km, Flyby ΔV = 771.5 m/s, Outbound, 47.8 days to T94											
OTM-356	T93+4d	30-Jul-2013 07:53	118.0	650.8	..... *CANCELLED*						

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

† Reported reconstructed ΔV values are based on preliminary OD estimates.

Table 1 presents the maneuver design and reconstruction history from June 3, 2012 through July 23, 2013, covering OTMs 325–356, where maneuvers are grouped by the corresponding targeted encounters. *Note:* OTM-325 was discussed in previous work[9] and OTM-356 will be covered in a future paper, and are included to provide context. The table lists the maneuver epoch, true anomaly, central angle, design and reconstructed ΔVs, and engine type. The reported true anomaly corresponds to the instantaneous Saturn-centered orbit at burn time; central angle corresponds to the three-dimensional angle between the position vectors at the burn time and encounter (counting multiple revolutions). The encounter rows contain the encounter name, time

of closest approach, flyby altitude, flyby ΔV imparted to spacecraft, whether flyby is inbound or outbound*, days to next encounter, and whether the target time was modified. Out of 30 opportunities (OTMs 326–355), 27 maneuvers were performed; 13 of which were implemented with MEA, 14 with RCS. The backup maneuver window for OTM-353 was performed, indicated as OTM-353 BU.

Table 2. Maneuver Window Characteristics (OTMs 325–356)

	Prime Maneuver Window						Backup Maneuver Window					
OTM	True Anom. (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	Burn Time (sec)	True Anom. (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (sec)	Burn Time (deg)
325	−140.22	287.89	0.0375	−61.81	−133.80	31.31	−125.45	273.12	0.0509	−66.48	−148.05	44.02
326	**158.82**	**693.46**	**0.4216**	**−168.31**	**−105.14**	**2.53**	**162.94**	**689.35**	**0.4910**	**−176.05**	**−89.41**	**2.94**
327	**−168.39**	**660.69**	**10.1186**	**98.62**	**−105.62**	**57.99**	**−165.03**	**657.34**	**10.2892**	**98.60**	**−105.17**	**58.97**
328	−128.20	260.42	0.1721	134.62	−152.52	158.89	−107.86	240.08	0.2613	120.81	−171.29	243.10
329	159.58	1050.54	0.0006	137.69	−94.60	0.87	164.30	1045.82	0.1014	110.18	−116.81	92.29
330	**−161.26**	**1011.39**	**4.3525**	**−121.08**	**−114.76**	**24.91**	**−156.07**	**1006.20**	**4.4243**	**−127.75**	**−116.22**	**25.32**
331	−107.20	237.36	0.0612	−47.16	−25.08	54.28	−9.96	140.09	0.0893	137.88	−49.59	81.40
332	152.89	685.28	0.1901	−158.54	−58.39	178.05	158.32	679.86	0.2192	−151.33	−55.78	206.02
333	**−168.14**	**646.32**	**0.7608**	**0.57**	**−22.11**	**4.47**	**−163.95**	**642.14**	**0.7336**	**16.20**	**−31.16**	**4.31**
334	−104.59	222.75	0.0600	−10.24	−173.93	53.14	−56.88	175.1	0.1270	−113.86	−144.17	117.88
335	**166.62**	**324.04**	**0.2548**	**93.40**	**−123.91**	**1.53**	**173.17**	**317.50**	**0.3875**	**101.13**	**−129.56**	**2.33**
336	**−161.00**	**291.66**	**4.9593**	**179.67**	**−140.76**	**28.35**	**−152.78**	**283.43**	**4.9079**	**167.23**	**−144.00**	28.06
337	−99.16	229.87	0.0219	56.28	−76.18	16.23	−13.55	144.25	0.0538	−98.34	−80.05	47.42
338	175.81	2118.92	0.0276	153.23	−142.38	21.80	−175.41	2110.15	0.0271	158.09	−144.98	21.33
339	**−106.70**	**601.60**	**1.6575**	**158.97**	**−110.96**	**9.61**	**−88.36**	**583.27**	**1.8524**	**156.09**	**−121.42**	**10.75**
340	−103.76	238.69	0.0323	136.22	−162.35	26.31	71.77	63.17	0.0838	−72.09	−94.52	76.48
341[B16]	**−112.12**	**431.33**	**1.4498**	**−72.71**	**−116.75**	**8.44**	**−84.08**	**403.31**	**1.4086**	**−72.63**	**−118.77**	**8.20**
342	**156.64**	**162.64**	**0.2644**	**126.02**	**−89.31**	**1.58**	**168.92**	**150.36**	**0.3467**	**113.84**	**−81.15**	**2.06**
343	−148.20	107.50	0.0189	100.21	−103.60	13.33	−130.53	89.84	0.0367	99.89	−110.61	30.86
344	121.35	737.66	0.0372	−26.74	−101.28	31.32	141.92	717.1	0.0449	−35.17	−100.04	38.93
345	−168.57	667.56	0.1859	−107.80	−116.51	175.78	−156.39	655.38	0.1949	−102.79	−97.02	184.49
346[*, B48]	−102.53	241.55	0.0166	−28.89	−34.85	11.0	58.48	80.55	0.0305	96.84	−82.56	24.76
347	−162.50	1757.02	0.1228	−33.47	−41.60	114.98	−146.39	1740.91	0.1295	−68.82	−6.24	121.60
348	**−117.90**	**992.45**	**0.4945**	**150.86**	**−138.09**	**2.94**	**−82.08**	**956.64**	**0.5293**	**139.27**	**−132.28**	**3.15**
349[*, B48]	−115.87	270.47	0.0169	−39.18	−48.52	11.37	87.42	67.22	0.0329	107.71	−84.21	27.06
350	−166.38	1385.14	0.0511	2.47	−12.46	45.03	−150.61	1369.38	0.0754	90.49	−25.53	68.89
351[B12]	**−82.33**	**941.21**	**0.8201**	**−31.88**	**−87.67**	**4.82**	**−26.36**	**885.3**	**1.1545**	**−22.95**	**−80.09**	**6.78**
352	16.19	122.7	0.0576	169.58	−63.15	51.77	76.11	62.8	0.0786	169.42	−93.31	72.48
353	163.5	298.0	0.2055	−154.10	−24.58	197.42	**177.9**	**283.7**	**0.2530**	**−91.13**	**−10.90**	**1.49**
354[B16]	**−119.4**	**221.0**	**2.2655**	**−13.71**	**−85.60**	**13.06**	**−105.6**	**207.2**	**2.2992**	**−15.52**	**−74.71**	**13.25**
355	4.3	97.2	0.0721	−16.97	−95.71	66.34	41.0	60.5	0.1063	−15.59	−86.18	100.19
356	118.0	650.8	0.0733	164.86	−63.88	67.49	130.0	638.8	0.0898	169.74	−62.75	83.78

[*] Prime maneuver design required a time-of-flight modification to make implementable.
[B#] The backup window was scheduled # hours after the prime window.

Table 2 lists the ΔV characteristics of each maneuver covered in the scope of this paper, including the maneuver location (true anomaly and central angle), the ΔV magnitude, the roll and yaw turn angles for burn orientation, and the burn durations. Each maneuver has both prime and backup designs. Backup maneuver windows are scheduled approximately 24 hours after the prime maneuver windows, unless noted. Data from executed maneuvers are shaded in gray, data from main engine maneuver designs are indicated in bold.

Table 3 provides the targeted encounter conditions, defined in the 110818 reference trajectory†, and the reconstructed flyby differences for each of the 11 flybys from T84 to T93, two of which had their time-of-closest approach modified (T90 and T91). This would bring the total of modified flybys in the Solstice Mission to 11, as compared to the Prime and Equinox Missions total of 6.

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

†The reference trajectory provides predetermined maneuver locations and flyby targets according to science sequence planning and objectives. 110818 is the release date of the reference trajectory update (August 18, 2011).

Table 3. Targeted Encounter History (Titan-84 to Titan-93)

Encounter	Flyby Characteristics			Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0)				Flyby Differences from Reference Trajectory		
	V_∞ ($\frac{km}{s}$)	Period (days)	Inc. (deg)	$\mathbf{B}\cdot\mathbf{R}$ (km)	$\mathbf{B}\cdot\mathbf{T}$ (km)	TCA (ET SCET)	Altitude (km)*	$\Delta\mathbf{B}\cdot\mathbf{R}$ (km)	$\Delta\mathbf{B}\cdot\mathbf{T}$ (km)	ΔTCA (sec)
Titan-84	5.45	23.9	21.1	−3496.63	1548.74	07-Jun-2012 00:08:27	959	0.76	1.87	−0.17
Titan-85	5.43	21.2	32.2	−2687.57	−2797.75	24-Jul-2012 20:04:14	1012	−0.61	0.42	−0.05
Titan-86	5.44	23.9	39.0	−3341.26	−1857.32	26-Sep-2012 14:36:45	956	−0.06	−0.18	0.03
Titan-87	5.42	16.0	46.3	1038.03	−3698.26	13-Nov-2012 10:23:15	973	1.40	−0.24	−0.01
Titan-88	5.42	13.3	53.0	−74.22	−3881.46	29-Nov-2012 08:58:06	1014	−0.28	−0.60	0.11
Titan-89	5.42	12.0	57.1	479.35	−4824.93	17-Feb-2013 01:57:42	1978	0.70	0.14	−0.003
Rhea-4†	9.27	12.0	57.1	−1537.16	−868.99	09-Mar-2013 18:18:34	1000	−3.00	6.88	−0.68
Titan-90‡	5.43	9.6	61.7	3534.49	−2394.42	05-Apr-2013 21:44:38	1400	0.01	0.06	−0.33 *(−0.3)*
Titan-91‡	5.44	12.0	59.4	−3211.28	−2098.69	23-May-2013 17:34:02	970	0.13	0.05	−0.23 *(−0.2)*
Titan-92§	5.44	16.0	56.7	−2897.67	−2505.31	10-Jul-2013 13:22:54	964	*0.33*	*0.38*	*−0.05*
Titan-93§	5.4	23.9	53.4	−3529.87	−2398.45	26-Jul-2013 11:57:29	1400	*0.39*	*0.38*	*0.01*

* Flyby altitudes were not explicitly targeted by maneuvers; reported altitudes are the reference trajectory values (relative to a sphere).
† Flyby differences from reference trajectory target conditions may appear large due to cancelled maneuvers.
‡ Time-of-flight purposefully modified; the quantity in parentheses denotes the difference from the reference trajectory.
§ Reported flyby differences are based on preliminary OD estimates.

ENDING THE SATURN AND RING OCCULTATIONS SUB-PHASE (IN-2A, T85–T90)

From July 2012 through April 2013, a series of short-period resonant Titan-to-Titan transfers (T85–T90), targeted by OTMs 326–346, increased the inclination from near zero to 61.7°. This time period spanned most of the first of three sub-phases in the *second inclined phase* (**In-2**) of the Solstice Mission, a sub-phase known as **In-2A**. The majority of ring and high latitude Saturn atmospheric occultations in the Solstice Mission occurred during this phase, including the last targeted flyby of Rhea. The following sections describe the maneuvers during this time frame, grouped by targeted encounter. Maneuvers of interest are highlighted.

Titan-84 to Titan-85 Flyby

OTMs 326, 327, and 328 were scheduled to target the outbound Titan-85 (T85) flyby, to increase the inclination to 32.2°. OTM-326 (MEA) and OTM-327 (MEA) were designed in an optimization chain and performed together to achieve the T85 target conditions. Because OTM-327 backup would add a non-trivial ΔV downstream cost of 0.57 m/s, OTM-327 prime was uplinked early to the spacecraft. OTM-328 (RCS) was the final approach maneuver to target T86, with a sizable ΔV of 0.17 m/s to correct OTM-327's T86 delivery error of ∼40 km a month earlier. Canceling this maneuver would cost a prohibitive 16.9 m/s, mostly reflected in the increased size of OTM-329. Because OTM-328 BU would be a borderline MEA burn of 0.26 m/s and add a cost of 0.24 m/s, an early uplink of the prime OTM-328 to the spacecraft was prioritized.

OTM-326, Return to Optimization Strategy and Switch to Main Engine OTM-326 was the first cleanup maneuver designed in an optimization chain with downstream maneuvers since OTM-284 in May 2011.[8] The reason behind this long gap in optimized cleanup maneuvers was the nature of the orbits from June 2011 through May 2012, which consisted of high Titan flybys and several Enceladus encounters. For these types

of orbits, a single impulse maneuver strategy is near optimal. During the design of OTM-325, the approach maneuver to the previous T84 flyby, it was expected a 1-σ delivery error of 2 km would result in a downstream cost of 0.5 m/s, mostly in the size of OTM-326 (see Figure 4). OTM-326 increased from a 0.12 m/s RCS maneuver to a 0.42 m/s MEA maneuver after the T84 flyby, which was missed by 2 km in the direction of OTM-325's delivery SMAA. This switch from RCS to MEA size for OTM-326 following a 1-σ flyby error also occurred with the cleanup maneuver OTM-257 in July 2010.[8]

OTM-327, Last Large Main Engine Burn Until 2014 OTM-327, a near-apoapsis shaping maneuver, was the only main engine burn over 10 m/s during the third year of the Solstice Mission. There are only three more large maneuvers planned: OTM-387 ($\sim$12) m/s in August 2014, OTM-438 ($\sim$8 m/s) in January 2016, and OTM-444 ($\sim$8 m/s) in March 2016. The last burn of this magnitude was OTM-249 in May 2010 (10.8 m/s).[7]

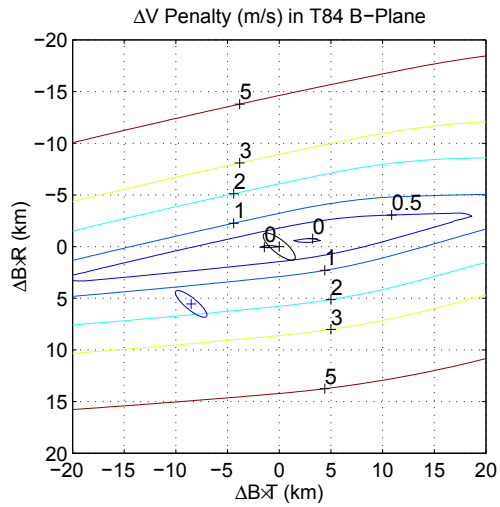


Figure 4. T84 Cost Contours (OTM-325)

Titan-85 to Titan-86 Flyby

OTMs 329, 330, and 331 were planned to target the outbound Titan-86 (T86) encounter, in order to increase the inclination to 39.0°. OTM-329 was cancelled because there was no downstream cost. OTM-330 (MEA) was targeted directly to the T86 flyby aimpoint. OTM-331 (RCS) was performed to correct a $\sim$4 km overshoot of T86 which would have resulted in a 1.46 m/s downstream cost (mostly reflected in the size of OTM-332).

OTM-329, Last Cancelled Maneuver for 7+ Months There were varying optimal solutions for OTM-329 with each OD solution, most likely because of multiple minima or the shape of the cost function was shallow near the solution such that multiple solutions appeared to exist. These types of sub-optimal solutions have been seen with past cleanup maneuvers, most recently with OTM-311, which was cancelled to save a downstream ΔV of $\sim$67 mm/s.[9] For the post-T85 flyby cases, the optimized cleanup maneuver solution had practically the same cost as placing all of the ΔV into OTM-330; hence, OTM-329 was cancelled. As seen in Figure 5, the T85 flyby miss of 1 km in $\mathbf{B} \cdot \mathbf{R}$ was along the zero-contour cost line. For an explanation of how each contour plot was produced, see Reference 17.

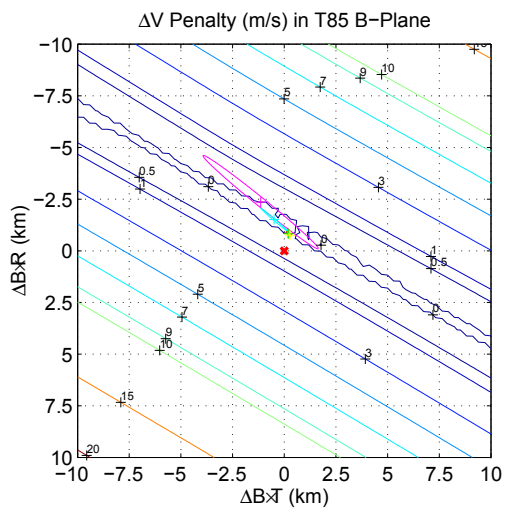


Figure 5. T85 Cost Contours (OTM-329)

OTM-330 and OTM-331, Changes to Burn Algorithms/Designs and Execution-Error Models From an execution-error analysis of maneuvers performed since January 2009, magnitude and pointing biases in the executions of main engine and RCS burns were identified. Starting with OTM-330 and OTM-331, a majority of these magnitude biases are now being removed via a flight software change or within the maneuver design process. Execution-error model updates that account for these removed biases were also first used in operations with these maneuvers (see execution-error model discussion in later section).

Titan-86 to Titan-87 Flyby

OTMs 332, 333, and 334 were planned to target the outbound Titan-87 (T87) flyby, to increase the inclination to 46.3°. OTM-332 (RCS) and OTM-333 (MEA) were designed in an optimization chain and performed together to achieve the T87 target conditions. Because OTM-332 would make half of the required B-plane changes, lumping OTM-332 into OTM-333 would add a cost of 3.1 m/s, mainly reflected in the sizes of OTMs 333 and 334. To avoid this downstream cost and missing the backup opportunity, OTM-332 was uplinked early to the spacecraft. OTM-334 (RCS) was performed to avoid a downstream penalty of 4.26 m/s, a cost to preserve the R4 flyby three encounters later.

OTM-333, Critical Plane Targeting Strategy for Backup Design The OTM-333 prime and backup designs for differed greatly, both in the size and direction of the ΔVs and in the resulting trajectories. Drastic differences were also seen with the OTM-081 prime and backup designs.[4,5] The nominal OTM-333 backup design yielded a downstream cost of 1 m/s, which would ensure the required asymptote at R4. By floating the T87 time-of-flight by $+3.8$ sec for the backup maneuver (determined via critical plane targeting), the downstream cost was reduced to only 0.13 m/s. The 'critical plane' is defined by the plane containing the $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ gradients. This strategy would have been used for the backup maneuver because the option to have OTM-334 target back to the original T87 time-of-closest approach was available.

Titan-87 to Titan-88 Flyby

OTMs 335, 336, and 337 were scheduled to target the outbound Titan-88 (T88) encounter, in order to increase the inclination to 53.0°. OTM-335 (MEA) and OTM-336 (MEA) were designed in an optimization chain and performed together to achieve the T88 target conditions. Canceling OTM-335 would have yielded a cost of 0.37 m/s. OTM-337 (RCS) was performed to correct a $\sim$4 km overshoot of T88 which would have resulted in a 0.93 m/s downstream cost (mostly reflected in the size of OTM-338).

OTM-335, Saving Hydrazine by Performing Small Main Engine Burn Following the T87 flyby, OTM-335 became a borderline MEA burn, now with the new lower-bound for the main engine burn time of $\sim$1.5 seconds set by OTM-318.[9] To save the hydrazine and limit RCS through-put, and because the subsequent large maneuver (OTM-336) would absorb OTM-335's delivery errors, the decision was made to execute OTM-335 with main engine.

OTM-336, Issues with Near-180° Roll Turn With a preliminary design of OTM-336, it was discovered that the flight rule for the main engine roll turn to be under 179.7° was violated. This flight rule is in place to constrain a roll turn in one direction, which may require an SID suspend depending on the direction of the turn. The final design for OTM-336 required a roll turn angle of 179.67°, just under the 179.7° flight rule and the closest to a 180° roll turn for main engine yet. Although the roll turn would not violate the flight rule, SID suspends were planned in the unlikely case that the roll turn was in the unpredicted direction.

OTM-337, SID Suspend Sequence Issue with Backup Maneuver There was a problem without resolution between an SID suspend sequence and the OTM-337 backup maneuver. With no easy resolution to this issue, the backup maneuver was deemed unviable and only the prime maneuver was approved by the Cassini project. Given this circumstance and the large downstream cost of 0.93 m/s if OTM-337 was not executed, OTM-337 was uplinked early to the spacecraft.

Titan-88 to Titan-89 Flyby

OTMs 338, 339, and 340 were planned to target the outbound Titan-89 (T89) flyby, to increase the inclination to 57.1°. This transfer would be the last with as many as six orbits until 2016. OTM-338 (RCS) and OTM-339 (MEA) were designed in an optimization chain and performed together to achieve the T89 target conditions, with OTM-339 doing the brunt of the aimpoint change. Canceling OTM-338 would have yielded a cost of 0.29 m/s. Delaying to the backup opportunity for OTM-339 would have added a 0.27 m/s downstream cost, mostly in the maneuver itself. Hence, OTM-339 was uplinked to the spacecraft earlier than scheduled. OTM-340 (RCS) was performed to correct a $\sim$10 km undershoot of T89 which would have resulted in a 3.44 m/s downstream cost (mostly reflected in the size of OTM-338). The backup design for

OTM-340 was ∼2-1/2 times larger in ΔV than the prime design and almost 180° in central angle travel from from the prime location (2 days later).

OTM-338, Decision to Constrain ΔV Direction for Future Sensitive Optimized Cleanup Maneuvers Because OTM-338 was small compared to OTM-339 (0.028 m/s vs 1.66 m/s), the optimal solution for OTM-338 was sensitive to slight changes to the OD solution (see OTM-329 discussion). This is most likely a numerical sensitivity caused by the presence of multiple solutions that add up to nearly the same total. This 'wobbling' is worse for RCS size designs, but it also happens for smaller ME size designs. For the first post-T88 maneuver design, wheel speeds were found acceptable. With more post-flyby tracking data, the direction of OTM-338 substantially changed, rendering the prior wheel speed strategy inadequate. Instead of rushing to find a new wheel speed solution for OTM-338, the maneuver was constrained to the prior ΔV direction which yielded favorable wheel speeds. The assumption is that a near optimal solution in the direction of the first post-flyby design should exist. Although the final maneuver design did not need to be constrained in the direction of the first post-flyby maneuver solution, it was in a similar direction. As a result of this experience, it was decided that future optimized cleanup maneuvers sensitive to OD solution would be constrained to the direction of the first post-flyby maneuver's direction.

Titan-89 to Rhea-4 Flyby

OTMs 341, 342, and 343 were planned to target the outbound Rhea-4 (R4) encounter, maintaining an inclination of 57.1°. R4 is the last planned targeted Rhea flyby of the Cassini mission; only three more non-targeted Rhea flybys will occur in 2015. OTM-341 (MEA) and OTM-342 (MEA) were designed in an optimization chain and performed together to achieve the R4 target conditions, with OTM-341 doing the brunt of the aimpoint change. OTM-341 was placed seven days after T89, not the typical three days for cleanup maneuvers. Using OTM-341 only to meet the R4 target conditions, effectively making OTM-342 a statistical maneuver to clean-up OTM-341's execution, would have added a 0.66 m/s cost, mainly in the growth of OTM-345 to a small main engine burn. Because of the necessity to perform OTM-341, a backup cost of 0.24 m/s, and more than two post-flyby tracks available to process, the prime OTM-341 was uplinked early to the spacecraft using the second post-flyby tracking pass data. Finally, there was no ΔV cost for canceling OTM-343 (RCS) (predicted savings of 23 mm/s) and no impact to Rhea science observations by the resulting ∼7 km target miss. Therefore, OTM-343 was canceled.

OTM-342, Saving Hydrazine by Performing as Small Main Engine Burn With a predicted 1.6 second burn duration above the 1.5 second threshold set by OTM-318, OTM-342 was executed as main engine to save the hydrazine required for RCS. The execution of OTM-342 would end a record 13-maneuver streak which began with OTM-330, surpassing the maneuver stretch set in 2007 with OTMs 128–139 following Iapetus-1.[4,5]

OTM-343, Canceling to Alter Upcoming Maneuvers OTM-343 presented an interesting situation: canceling OTM-343 would not incur a downstream cost and the next two maneuvers, OTMs 344 and 345, would swap in ΔV magnitudes. Given the execution of OTM-343, OTM-344 would be a sizable 0.13 m/s to a 0.06 m/s OTM-345; this would lead to the possibility of having OTM-344 target directly the T90 flyby (but OTM-345 would probably be needed to clean-up execution errors). On the other hand, given the cancellation of OTM-343, OTM-345 would be a sizable 0.12 m/s to a 0.04 m/s OTM-344; this would increase the chance of having OTM-345 solely target the T90 flyby. The possible double cancellation of OTMs 343 and 344 was the most attractive of the two; thus, OTM-343 was cancelled.

Rhea-4 to Titan-90 Flyby

OTMs 344, 345, and 346 were scheduled to target the outbound Titan-90 (T90) flyby, achieving a peak inclination of 61.7°. Beginning with T90, there will be only targeted Titan flybys (23 in total) until June 2015 with Dione-4. Cancelling OTM-344 would introduce a small deterministic downstream cost of ∼77 mm/s, but not all of this cost would go into RCS burns and increase the hydrazine usage. Also, the prime and backup OTM-344 designs would require the insertion of additional RWA biases to control the wheel speeds, For these reasons, OTM-344 was cancelled and OTM-345 (RCS) was used to target T90 directly. OTM-346

(RCS) was performed to avoid a 0.27 m/s downstream cost, introducing a T90 time-of-flight change of -0.3 seconds to bring the ΔV to an implementable size.

*OTM-346, Time-of-Flight Change to Make Implementable Maneuver*The initial design of OTM-346 was too small to implement at $\sim$6 mm/s (RCS ΔV must be larger than 9 mm/s). Because of a OTM-346 cancellation cost of 0.27 m/s, the time-of-flight at T90 was modified by -0.3 seconds to increase the ΔV to 10.8 mm/s (excluding the 5.8 deadbanding tightening, etc. ΔV added to the burn). The backup design, which was placed two days after the prime location to distance it from periapsis, did not require a modification to the time-of-flight to make implementable and would only cost $\sim$64 mm/s over the prime. However, this backup cost was considered non-trivial. The decision to adjust the T90 time of flight was facilitated using a plot of maneuver ΔV vs encounter TF change shown in Figure 6.

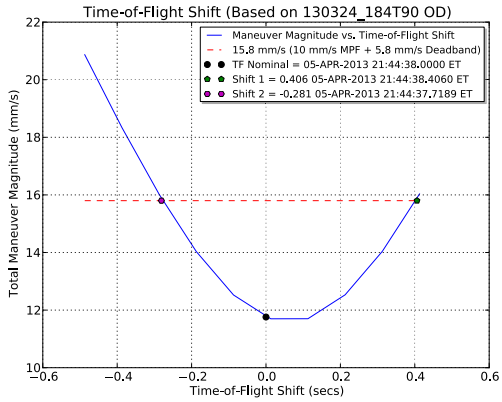


Figure 6. T90 Time-of-Flight Shift

BEGINNING THE MAGNETOTAIL PASSAGE SUB-PHASE (IN-2B, T91–T93)

From May 2013 through May 2014, a series of resonant and generally longer period orbits (most $>$ 32 days) reduces inclination from 61.7° to 40.7°. This sub-phase of the *second inclined phase* (**In-2B**) was designed to provide both northern and southern hemisphere, low phase Titan surface coverage and multiple inclined passages through Saturn's magnetotail region.[1] The maneuvers targeting the first three Titan flybys in this phase, T91–T93, are discussed in this section. Maneuvers of interest are highlighted.

Titan-90 to Titan-91 Flyby

OTMs 347, 348, and 349 were planned to target the outbound Titan-91 (T91) flyby, decreasing the inclination to 59.4°. OTM-347 (RCS) and OTM-348 (MEA) were designed in an optimization chain and performed together to achieve the T91 target conditions, with OTM-348 doing the brunt of the aimpoint change. OTM-347 was executed near apoapsis and OTM-348 near periapsis; neither one of which could be performed alone to accomplish the T91 target. OTM-349 (RCS) was performed to avoid a 0.72 m/s downstream cost, introducing a T91 time-of-flight change of -0.2 seconds to bring the ΔV to an implementable size.

OTM-347, First Time to Employ Constrained ΔV Direction Strategy for Optimized Cleanup Maneuvers Given the longer computation time and the need to iterate with SCO for wheel speeds, OTM-347 was constrained to the direction computed for the first post-T90 solution. (Note, the magnitude of the cleanup maneuver is still optimized with the next maneuver.) This strategy for small optimized cleanup maneuvers was adopted at the time of OTM-338.

OTM-349, Time-of-Flight Change to Make Implementable Maneuver Like OTM-346, the initial design of OTM-349 was too small to implement at $\sim$7 mm/s. Because of a OTM-349 cancellation cost of 0.72 m/s, the time-of-flight at T90 was modified by -0.2 seconds to increase the ΔV to 10.8 mm/s (excluding the 5.8 deadbanding tightening, etc. ΔV added to the burn). The backup design, which was placed on the other side of periapsis two days after the prime location, did not require a modification to the time-of-flight to make implementable and would cost $\sim$70 mm/s

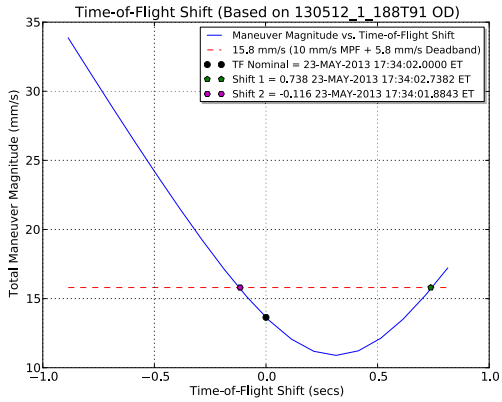


Figure 7. T91 Time-of-Flight Shift

over the prime. However, this backup cost was considered non-trivial. The T91 time of flight modification choice was based on a plot of maneuver ΔV vs encounter TF change shown in Figure 7.

Titan-91 to Titan-92 Flyby

OTMs 350, 351, and 352 were scheduled to target the outbound Titan-92 (T92) flyby, reducing the inclination to 56.7°. OTM-350 (RCS) and OTM-351 (MEA) were designed in an optimization chain and performed together to achieve the T92 target conditions, with OTM-351 doing the brunt of the aimpoint change. OTM-350 was executed to avoid a 0.091 m/s downstream cost, mostly reflected in the size of OTM-351. Because the backup opportunity for OTM-351 yielded a significant penalty of 0.38 m/s over the prime and increased the chance of an impacting trajectory, OTM-351 was uplinked early to the spacecraft. OTM-352 (RCS) was performed to correct a $\sim$12 km undershoot of T92 which would have resulted in a 2.2 m/s downstream cost (mostly reflected in the increased sizes of OTMs 353 and 356).

OTM-350, Cleanup Maneuver Design Based on First Post-Flyby Track The final design for OTM-350 was based on the first post-flyby tracking data to facilitate wheel speed management and short turn-around times. This procedure will be used for future cleanup maneuvers when the following maneuvers are substantially larger. Any multi-σ in the OD solution with the next post-flyby track, if available, will be swamped by the execution errors of the next maneuver.

Titan-92 to Titan-93 Flyby

OTMs 353, 354, and 355 were planned to target the outbound Titan-93 (T93) flyby, decreasing the inclination to 53.4°. This would be the last 16-day Titan-to-Titan transfer until 2015. OTM-353 BU (MEA) and OTM-354 (MEA) were designed in an optimization chain and performed together to achieve the T93 target conditions, with OTM-354 doing the brunt of the aimpoint change. OTM-353 was executed at the backup opportunity to avoid a 0.22 m/s downstream cost and to save the equivalent hydrazine required to perform at the prime opportunity ($\sim$220 grams). OTM-355 (RCS) was performed to correct a $\sim$15 km overshoot of T93 which would have resulted in a 4 m/s downstream cost, mainly in OTM-356.

OTM-353, Saving Hydrazine by Performing Backup as Small Main Engine Burn Prior to the T92 flyby, OTM-353 was around 0.16 m/s. It grew to 0.21 m/s following the T92 encounter, yielding a cancellation cost of 0.22 m/s. The backup design ΔV also increased following the T92 flyby from 0.21 m/s to 0.27 m/s. RCS burns can be designed up to 0.3 m/s, but given the 0.25 m/s main engine burn precedent set by OTM-318 and the two like-sized main engine maneuvers that followed (OTMs 335 and 342), the backup maneuver was redesigned as a main engine burn. With the spin-up/spin-down ΔV events modeled, the backup ΔV reduced to 0.25 m/s, within the lower main engine burn bound. Because there was no cost to deferring to the backup opportunity, the decision to execute the OTM-353 backup was based solely on a trade-off between consuming hydrazine (RCS) over bi-propellant (MEA). For OTM-353 prime at 0.27 m/s, it would have required an equivalent 270 grams of hydrazine. Interestingly, this was only the second time a backup maneuver was performed on main engine, the first time being OTM-123 BU in August 2007.

EXECUTION-ERROR MODEL UPDATES AND CHANGES TO MANEUVER EXECUTIONS

Maneuver reconstructions are used to assess the performance of Cassini's main engine and RCS thrusters. From such assessments, it is possible to develop reasonable models of the maneuver execution errors (magnitude and pointing errors), and to identify biases seen in the maneuver executions.[18] Representative execution-error models of the maneuvers can be used to understand future maneuver performance, while providing means for detecting degradation in either propulsion or attitude control. Updates to the execution-error models for Cassini's main engine and RCS maneuvers were developed and first used in maneuver operations in August 2012,[10,11] replacing the previous 2008-01 model.[19] In conjunction with these execution-error model updates, magnitude biases were removed either through a flight software change or within the maneuver design process. Identified pointing biases were not removed, but are accounted for in the execution-error models. This section discusses the 2012-1 Execution-Error Models and the maneuver performance following

the August 2012 execution changes to main engine and September 2012 changes to RCS maneuvers through July 7, 2013, covering 9 main engine burns and 12 RCS maneuvers.

Table 4. 2012-1 Execution-Error Models (1-σ). Valid for MEA burns $\leq$ 13 m/s and RCS burns $\leq$ 0.3 m/s.

		Main Engine	RCS
Magnitude	Proportional (%)	0.02	0.4
	Fixed (mm/s)	3.5	0.5
Pointing (per axis)	Proportional (mrad)	1.0	4.5
	Fixed (mm/s)	5.0	0

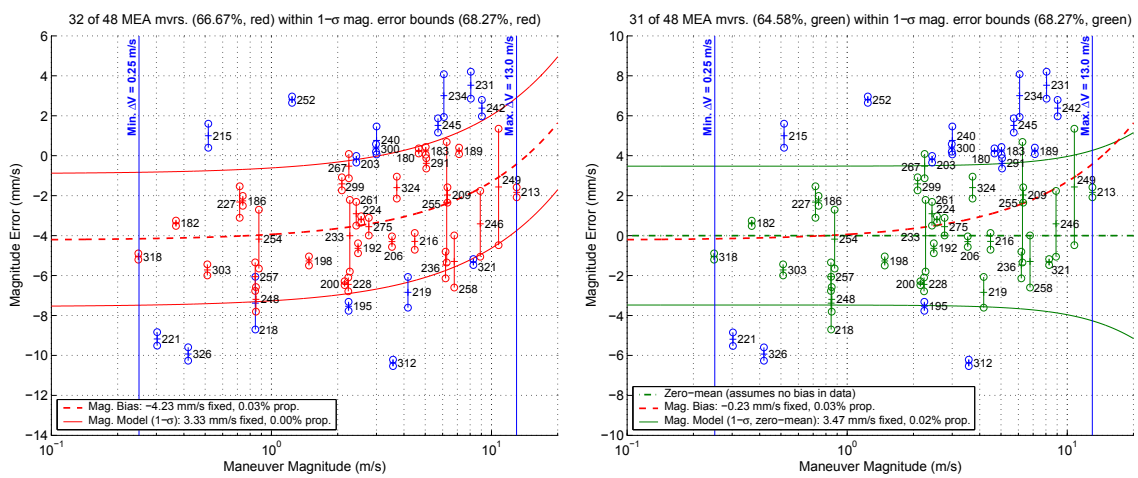
Table 4 lists the main engine and RCS maneuver execution-error model updates. The 2012-1 main engine model was developed from an analysis of 48 main engine maneuvers following propulsion's January 2009 fuel-side repressurization through June 2012 (OTMs 180–326) and is documented in Reference 10. The 2012-1 RCS model was developed from an analysis of 49 RCS maneuvers following the March 2009 thruster branch swap through July 2012 (OTMs 183x–328) and is documented in Reference 11.

Execution-Error Modeling

The Gates execution-error model accounts for four independent error sources: fixed and proportional-magnitude errors and fixed and proportional-pointing errors. The direction of pointing errors is assumed to have a uniform distribution across 360°. Each of the four sources is assumed to have a Gaussian distribution, so each parameter represents the standard deviation for that error source and each error source is assumed to have a zero mean. Via a weighted maximum-likelihood estimator, the Gates execution-error model parameters[15] and corresponding biases in execution for the main engine and RCS maneuvers, processed separately, are computed. For more information on the Cassini execution-error modeling process, see Reference 18.

Main Engine Execution-Error Analysis (2012-1 Model Update)

The 2012-1 main engine model represents the execution errors seen with main engine burns following Cassini's last fuel-side repressurization in January 2009.



(a) With −4 mm/s fixed-magnitude bias

(b) Removed −4 mm/s fixed-magnitude bias

Figure 8. Main Engine Magnitude Error vs. Maneuver Magnitude (2012-1 Study, OTMs 180–342). 1-σ error bars are red for burns within 1-σ magnitude-error bounds, green for burns inside of zero-mean 1-σ bounds, and blue for burns outside of 1-σ bounds.

Figure 8 illustrates magnitude error as a function of maneuver magnitude for the main engine maneuvers considered in the 2012-1 study. The estimated magnitude bias and the 1-σ error bounds about the magnitude bias, given by the execution-error model, are plotted in each figure. The error bars about the maneuver data points represent the 1-σ uncertainties in the OD estimates of the magnitude errors. These uncertainties were used to weight each maneuver in the maximum-likelihood estimator. It is assumed with the Gates model that the magnitude errors follow a normal distribution; hence, for a one-dimensional distribution, it is expected that 68% of the maneuvers will fall within the 1-σ magnitude bounds (the actual number of maneuvers within the bounds is indicated in each plot).

Figure 8(a) shows the magnitude errors and magnitude-error model/bias lines with the observed -4.2 mm/s fixed-magnitude and 0.03% proportional-magnitude biases, and Figure 8(b) the magnitude errors and the zero-mean magnitude-error model lines (i.e., model assumes no bias in magnitude) after removing -4 mm/s of the fixed-magnitude bias via adjustments to the expected ΔV data. In both cases, the computed magnitude-error model assumes that the estimated fixed and proportional-magnitude biases are removed. Although the proportional-magnitude bias term remains, a zero-mean model is necessary in Cassini operations because the orbit determination filter assumes Gaussian execution errors about the maneuver design values and does not have visibility into any underlying biases in the errors. The -4 mm/s fixed-magnitude bias was effectively removed from future main engine executions via a flight software patch to the tail-off impulse parameter in July 2012. Similarly, a -3 mm/s bias in fixed magnitude was seen with the previous 2008-01 execution-error analysis[19] and corrected with a change to the tail-off impulse parameter in April 2009.

Without the magnitude-error adjustments, the main engine maneuvers showed a tendency to underburn (37 of 48 maneuvers, 77%). Accounting for the July 2012 FSW patch to the tail-off impulse parameter in the magnitude errors resulted in a more even distribution of underburns (21 of 48 maneuvers, 44%) and overburns (27 of 48 maneuvers, 56%).

Main Engine Maneuver Performance from August 2012 to June 2013 (OTMs 330-351)

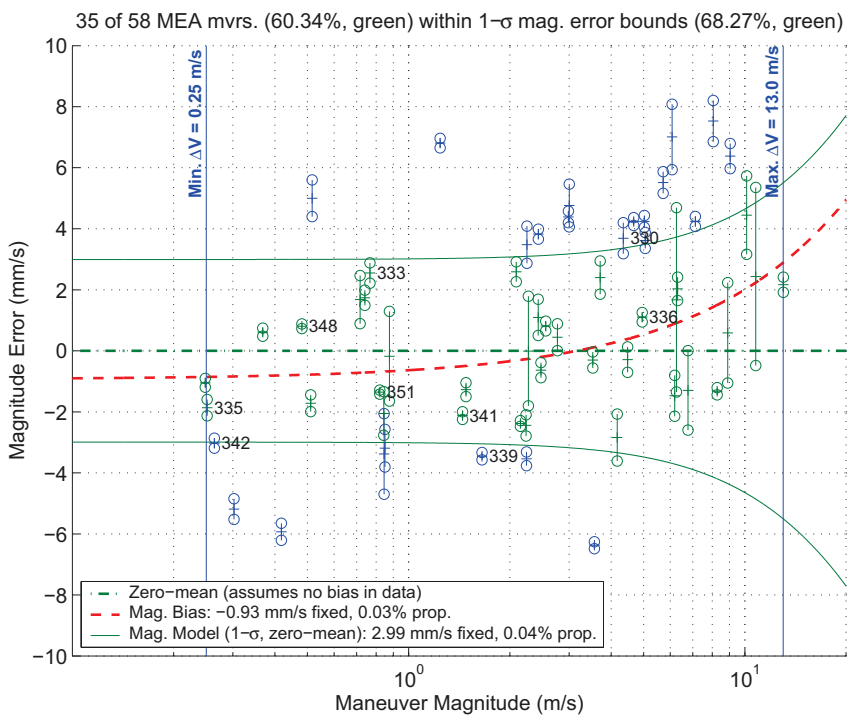
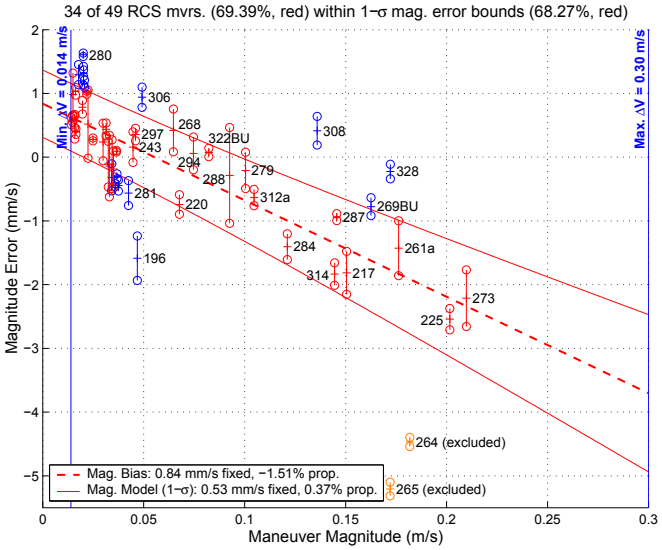


Figure 9. Main Engine Magnitude Error vs. Maneuver Magnitude (2013-1 Study, OTMs 180–351). 1-σ error bars are green for burns inside of zero-mean 1-σ magnitude-error bounds and blue for burns outside of 1-σ bounds.

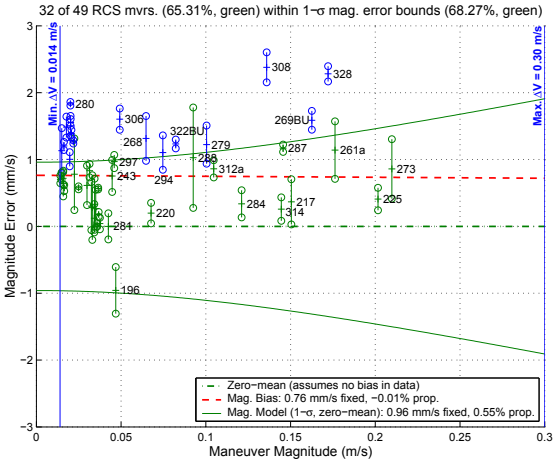
As seen in Figure 9, the magnitude-error uncertainties of the 2012-1 main engine model holds well given the performance of nine main engine burns from August 2012 to June 2013 (OTMs 330–351). This also implies that the -4 mm/s fixed-magnitude bias was correctly identified and that the flight software patch to the main engine tail-off impulse parameter was effective in removing this bias. One benefit of removing the fixed-magnitude bias is that the magnitude errors will be more equally distributed about zero (not entirely because a small proportional-magnitude bias was not removed). Most magnitude errors can now be expected to fall within ± 4 mm/s, which was the case for all maneuvers considered in this performance study.

RCS Execution-Error Analysis (2012-1 Model Update)

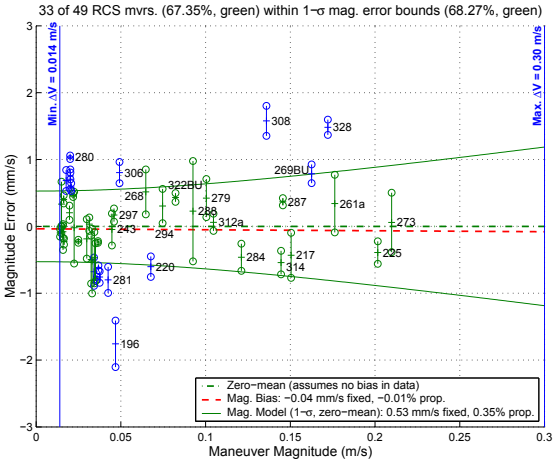
The 2012-1 RCS model is the first to characterize the execution errors seen with RCS maneuvers executed via the redundant B-branch thrusters, the main A-branch thrusters relegated to backup in March 2009 because of a marked degradation in performance.



(a) With -1.5% prop-mag and $+0.8$ mm/s fixed-mag biases



(b) Removed -1.5% prop-mag bias only



(c) Removed -1.5% prop-mag and $+0.8$ mm/s fixed-mag biases

Figure 10. RCS Magnitude Error vs. Maneuver Magnitude (2012-1 Study, OTMs 183x–328). 1-σ error bars are red for burns within 1-σ magnitude-error bounds, green for burns inside of zero-mean 1-σ bounds, and blue for burns outside of 1-σ bounds.

Figure 10 illustrates magnitude error as a function of maneuver magnitude for the RCS maneuvers considered in the 2012-1 study. The estimated magnitude bias and the 1-σ error bounds about the magnitude bias, given by the execution-error model, are plotted in each figure. The error bars about the maneuver data points represent the 1-σ uncertainties in the OD estimates of the magnitude errors, which were used to weigh each maneuver in the maximum-likelihood estimator.

Figure 10(a) displays the magnitude errors and the magnitude-error model/bias lines with the observed -1.5% proportional-magnitude and +0.8 mm/s fixed-magnitude biases, and Figure 10(b) the magnitude errors and the zero-mean magnitude-error model lines with the observed +0.8 mm/s fixed-magnitude bias only, after removing -1.5% of the proportional-magnitude bias via adjustments to the expected ΔV data. With the zero-mean magnitude-error model, nearly all maneuvers would be considered an overburn, in some cases 1-σ to 2-σ overburns. Unlike the main engine magnitude-error model, not removing one of the magnitude biases would result in an unbalanced ratio of overburns to underburns.

Figure 10(c) shows the magnitude errors and the zero-mean magnitude-error model lines after removing both the fixed and proportional-magnitude errors, $+0.8$ mm/s and -1.5%, respectively, via adjustments to the expected ΔV data. The observed proportional-magnitude bias was removed by Propulsion via a -1.5% adjustment to the RCS FADJ (thrust adjustment) factor, from 0.98 to 0.965. The fixed-magnitude bias was removed by Navigation by adding 0.8 mm/s to the 5.0 mm/s deadband-tightening ΔV which is currently specified in the RCS maneuver designs. This updated value of 5.8 mm/s serves as both a correction for the average deadband-tightening ΔV observed by Navigation and the fixed-magnitude bias seen in RCS maneuver executions.

Without the magnitude-error adjustments, the RCS maneuvers showed a slight tendency to overburn (26 of 49 maneuvers, 53%). Accounting for the September 2012 FADJ factor adjustment and the +0.8 mm/s fixed-magnitude correction resulted in a more even distribution of overburns (24 of 49 maneuvers, 49%) and underburns (25 of 49 maneuvers, 51%).

RCS Maneuver Performance from September 2012 to July 2013 (OTMs 331–352)

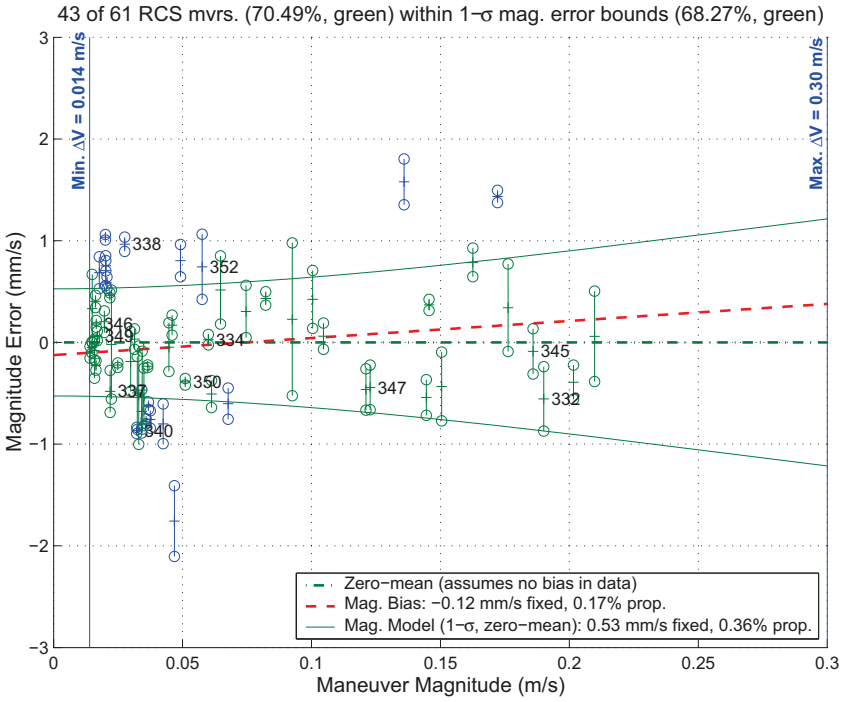


Figure 11. RCS Magnitude Error vs. Maneuver Magnitude (2013-1 Study, OTMs 183x–352). 1-σ error bars are green for burns inside of zero-mean 1-σ magnitude-error bounds and blue for burns outside of 1-σ bounds.

As seen in Figure 11, the magnitude-error uncertainties of the 2012-1 RCS model holds well given the performance of 12 RCS maneuvers from September 2012 to July 2013 (OTMs 331–352). This great performance implies that the fixed and proportional-magnitude biasese were correctly identified and that the changes to the RCS design process was effective in removing these biases. One advantage of removing the magnitude biases is that the magnitude errors should be equally distributed about zero. Most magnitude errors can now be expected to fall within ± 1 mm/s, which was the case for all maneuvers considered in this performance study.

NAVIGATION COST ANALYSIS

Table 5. Maneuver Performance per Encounter

Encounter Span	Ref. Traj. Det. ΔV (m/s)	Predicted ΔV Statistics Mean (m/s)	1-σ (m/s)	90%* (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Navigation ΔV Cost† (m/s)
T83–T84	3.720	3.928	0.180	4.181	3.752	3.750	**0.029**
T84–T85	10.123	10.954	0.507	11.666	10.712	10.703	**0.579**
T85–T86	4.282	5.277	0.650	6.161	4.414	4.417	**0.136**
T86–T87	0.806	1.904	0.706	2.883	1.011	1.013	**0.207**
T87–T88	5.060	5.903	0.677	6.846	5.236	5.235	**0.175**
T88–T89	1.694	2.295	0.492	2.978	1.717	1.714	**0.020**
T89–R4	1.525	2.359	0.656	3.251	1.714	1.709	**0.184**
R4–T90	0.139	0.355	0.249	0.658	0.202	0.203	**0.063**
T90–T91	0.422	0.898	0.387	1.430	0.634	0.635	**0.213**
T91–T92	0.886	1.716	0.672	2.609	0.929	0.928	**0.042**
T92–T93	2.390	3.068	0.551	3.818	2.591	*2.589*	*0.199*

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

Table 5 shows the maneuver performance per flyby, by comparing the reconstructed ΔV from each encounter span to the planned ΔV from the reference trajectory (see shaded columns). This maneuver performance is represented by the navigation ΔV cost per flyby (see last column). The predicted ΔV statistics per flyby were garnered from statistical analyses reported in Reference 16 and later updated in operations.

Table 6. Average Navigation ΔV Cost per Encounter

Mission	Flyby Span	Number of Flybys	Nav. Cost per Flyby Average (m/s)	Std. Dev. (m/s)
Prime (7/2004 – 9/2008)	Ta–E4	54	0.324	0.594
Equinox (9/2008 – 9/2010)	E5–T72	36	0.447	0.978
Solstice (9/2010 – 7/2013, First 3 Years)	T73–T93	32	*0.131*	*0.142*

The average navigation ΔV cost per flyby is summarized in Table 6. The cost between each encounter was not as evenly distributed prior to the Solstice Mission, a fact that can be seen in the large standard deviation of nearly 1 m/s for the Equinox Mission reported in the table. With the majority of the maneuvers performed on RCS during the Solstice Mission, the average navigation cost so far in the has been less than half the average cost seen in the prior missions.

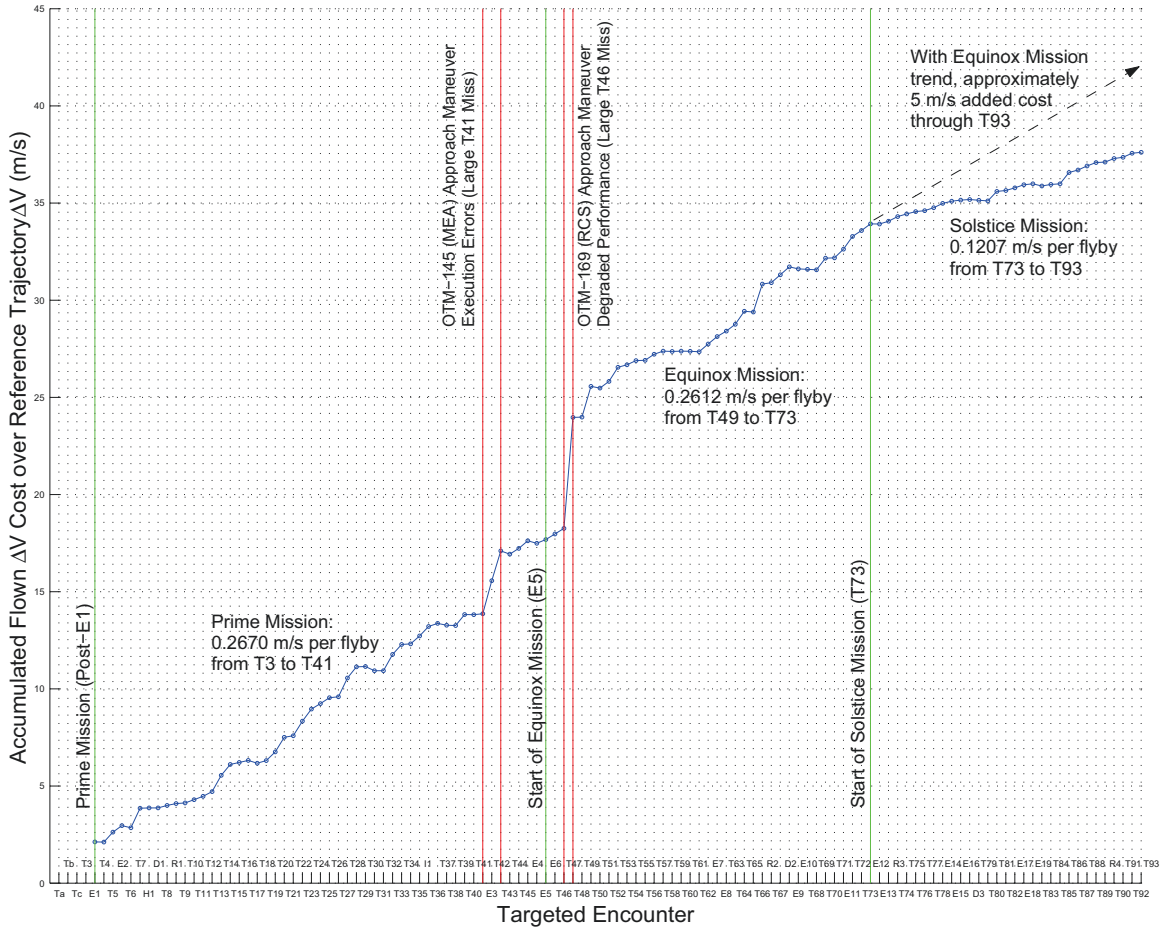


Figure 12. Accumulated Flown ΔV Cost over Reference Trajectory

From Figure 12, it can be seen that from the start of the Solstice Mission, the upward Navigation cost trend had been curbed. Without the refinements in the maneuver decision process, it is likely that the trend set by the Prime and Equinox Missions would have continued, accounting for an additional 5 m/s in the past 3 years. As noted in the figure, the large execution errors following approach maneuvers OTM-145 and OTM-169 resulted in significant ΔV penalties totaling nearly 10 m/s, twice the Solstice Mission's 5 m/s savings. Given how detrimental these types of execution errors can be on the propellant margin, actively re-evaluating the maneuver implementation strategy is now an important key to ensuring the 2017 end-of-mission goal.

END-OF-MISSION OUTLOOK

The third year of Solstice Mission maneuver operations was marked by the percentage of planned maneuvers performed. Out of 30 maneuver opportunities, 27 were executed (90%). This high percentage is dependent on the type of flybys during this time period (low outbound Titan flybys, one low Rhea encounter), but is likely to continue as Navigation strives to adhere to the reference trajectory. With mostly low Titan flybys through 2015, this trend of few maneuver cancellations is expected to continue.

Throughout the Prime and Equinox Missions, small cleanup maneuvers followed by large apocrone maneuvers tended to be cancelled. The cleanup maneuvers are the main mechanism for controlling the flyby asymptote errors; consecutively canceling these maneuvers would produce larger downstream asymptote differences from the reference trajectory and potentially create a sizable 'negative' region in ΔV cost with an aimpoint change, meaning a small target change could result in a substantial ΔV savings, typically over 1

m/s (as represented by the larger dips in Figure 12). During the Prime Mission, the strategy of 'kicking the can down the road' would usually continue until a cleanup maneuver grew to a main engine maneuver (> 0.3 m/s). One of the main Solstice Mission strategies is to fly Cassini as close to the prescribed trajectory as possible, in an effort to preserve fuel, particularly hydrazine. Hydrazine is the limiting factor for maneuvers; all maneuvers and spacecraft pointing and wheel management can be accomplished via RCS, the converse is not true. Because of hydrazine consumption and RCS thruster degradation concerns, performing small main engine burns as opposed to large RCS maneuvers (see OTMs 318, 335, 342, and 353 BU) is now the preferred route. As a consequence of this rationale change, it is unlikely that the large negative regions of > 1 m/s of the past will be seen again.

As the end-of-mission approaches, a few measures to address a dwindling work-force have been taken. Starting with OTM-339 maneuver operations in December 2012, the decision to not process every tracking pass was made, resulting in a reduced OD solution delivery schedule of once or twice a week during long periods between maneuver opportunities, acceptable since satellites are now well known. Because the prime maneuver opportunities were generally placed at optimal times, the backup windows would sometimes not be as effective, especially if the maneuver was designed to be executed near periapsis. To mitigate the possibility of missing the prime window for a maneuver with a costly backup, early uplinks of a prime maneuver design became more commonplace in recent operations. Early uplinks also extended to planned backup maneuvers such as OTM-353 BU. The Cassini Project now prefers saving hydrazine over adding maneuver cycles to the spacecraft, which translates to a higher rate of performed maneuvers and a closer adherence to the prescribed trajectory. OTM-280, an approach performed in the first year of the Solstice Mission, set the precedent of performing a maneuver to avoid a small downstream cost of 70 mm/s or over (in this case 77 mm/s, an equivalent of 77 grams of hydrazine).[8]

CONCLUDING REMARKS

Nearly half-way into the 7-year Solstice Mission, the Cassini Project continues to re-evaluate its maneuver decision and cancellation process. During the Prime and Equinox Missions, the health of the propulsion systems was prioritized over any projected downstream savings by executing a maneuver. As Cassini approaches the 2017 end-of-mission date, preserving fuel is now a priority over adding maneuver cycles. The concern for maneuver cycles still exists under the scrutiny of managing the RCS, since RCS is also required for attitude control, pointing Cassini's high-gain antenna to Earth for communication, and reaction wheel calibrations, without any of which the mission would abruptly end. In that regard, maneuvers that can be accomplished with main engine are now preferred. Already four small main engine burns since April 2012 have been performed where as in the past they would have been designed as large RCS burns. Most opportunities to save small downstream costs are now taken, in the hope that these savings will translate into hydrazine reserves for RCS usage. Maneuver operations during June 2012 through July 2013 has been a prime example of this new direction. Only 10% of planned maneuvers were cancelled in order to fly closely to the reference trajectory and reduce overall fuel usage. With four more years planned in the Solstice Mission, the Cassini Navigation Team will continue to maintain the prescribed Saturn tour through the execution of maneuvers that will enable the science requirements of the mission.

ACKNOWLEDGMENTS

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