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# CASSINI SOLSTICE MISSION MANEUVER EXPERIENCE: YEAR ONE

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The Cassini-Huygens spacecraft began its four-year Prime Mission to study Saturn's system in July 2004. Two tour extensions followed: a two-year Equinox Mission beginning in July 2008 and a seven-year Solstice Mission starting in September 2010. This paper highlights Cassini maneuver activities from June 2010 through June 2011, covering the transition from the Equinox to Solstice Mission. This interval included 38 scheduled maneuvers, nine targeted Titan flybys, three targeted Enceladus flybys, and one close Rhea flyby. In addition, beyond the demanding nominal navigation schedule, numerous unforeseen challenges further complicated maneuver operations. These challenges will be discussed in detail.

## OVERVIEW

The Cassini-Huygens spacecraft was launched in October 1997 on a mission to observe Saturn and its moons. After a seven-year interplanetary cruise, Cassini entered orbit around Saturn in July 2004 and began a nominal four-year tour, also known as the Prime Mission. In December 2004, the Huygens probe was released from the Cassini orbiter for a successful descent and landing on the surface of Titan in January 2005. After several years of successful operations, two subsequent extended missions were approved: the two-year Equinox Mission, from July 2008 through September 2010, and the seven-year Solstice Mission, which began on September 27, 2010 and is planned to conclude in September 2017. The Solstice Mission extends the mission lifetime past Saturn's northern summer solstice in May 2017 in order to increase the temporal baseline observable to two Saturnian seasons.[1] The demanding maneuver schedule set by the Prime and Equinox Missions, yielding over 200 executed maneuvers,[2,3] continues in the Solstice Mission with 205 maneuver opportunities[4] spread over seven years. With 70 targeted flybys of Titan, Enceladus, Dione, and Rhea, the Solstice Mission almost doubles the number of targeted encounters, and consequently, the number of maneuvers required thus far.

This paper focuses on the maneuver activities of the Cassini orbiter from June 8, 2010 through June 24, 2011, a period which included 38 planned Orbit Trim Maneuvers (OTMs). It spans the concluding four months of the Equinox Mission and the first nine months of the Solstice Mission. Earlier papers from the Cassini Maneuver Team reported on the maneuver experience during Cassini's interplanetary cruise to Saturn,[5–7] the four years of the Prime Mission,[8–11] and 23 of the 27 months of the Equinox Mission.[12,13]

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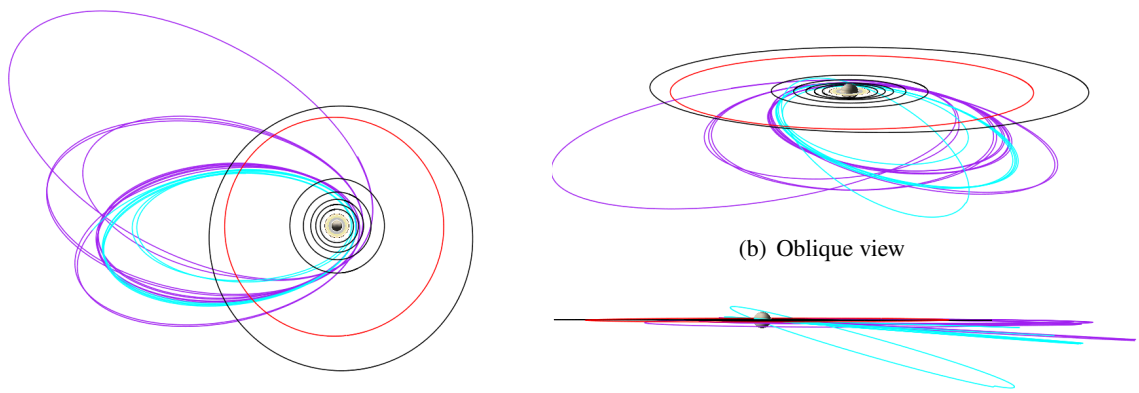
As illustrated in Figure 1, the transition from the Equinox to the Solstice Mission included inclination reduction and equatorial phases. The planned maneuvers, OTM-251 through OTM-287, targeted the Cassini orbiter to flyby aimpoints near Titan, Enceladus, and Rhea, as outlined in Reference 4. The last four months of the Equinox Mission (June–September 2010) consisted of resonant Titan-to-Titan transfers which decreased the orbit inclination from the initial 19.1° to 3.0° in order to set up the first equatorial phase of the Solstice Mission, as can be seen with the gray spacecraft orbits in Figure 1(c).[1] The first nine months of the Solstice Mission were comprised of equatorial orbits used to stage several Saturn high-latitude occultations and icy moon targeted flybys through May 2012, most of which were of Enceladus. Also, the orbit petal rotation made during this phase establishes the spacecraft orbit node required to achieve Saturn and ring occultations in the next phase beginning in May 2012. This paper covers encounters to Titan-77 (T77) on June 20, 2011, and includes three of the 10 icy satellite flybys of this phase: two Enceladus and one Rhea.



(a) Saturn North Polar View (Sun fixed, towards top of page)

(b) Oblique view

(c) View from within Saturn's Equatorial plane

**Figure 1. Spacecraft Trajectory: End of Equinox Mission (June–Sept. 2010) in gray, Start of Solstice Mission (Oct. 2010–June 2011) in purple.** The red circle is the orbit of Titan. The black circles are the orbits of select icy satellites (Mimas, Enceladus, Tethys, Dione, Rhea, and Hyperion).

Five rarely seen or first-time events occurred within just the first few months of the Solstice Mission: spacecraft safing; OTM-265, a Reaction Control Subsystem (RCS) maneuver, required RCS-controlled turns due to the safing event; OTM-267 returned the spacecraft to Reaction Wheel Assembly (RWA) control; OTM-268 reverted to a design based on a preliminary orbit determination solution; and OTM-269 was performed at the backup window. This paper presents the significance of these and other first-time or rarely seen events.

To ensure that science objectives are met remains a primary task of Navigation throughout the Saturn tour. However, with seven years added to the tour via the Solstice Mission, saving hydrazine by performing scheduled maneuvers began to outweigh concerns of adding maneuver cycles to the spacecraft. Hydrazine is used when orienting Cassini for main engine burns. More importantly, hydrazine is necessary for attitude control and pointing the spacecraft's high-gain antenna to Earth for communication. Propellant preservation to better guarantee a mission completion in 2017 was achieved in large part by target modifications, a practice that was often recommended, but not widely accepted until this time.

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.[14] For example, on revolutions 140 and 141, OTMs 266, 267, and 268 target Enceladus-12 (E12).

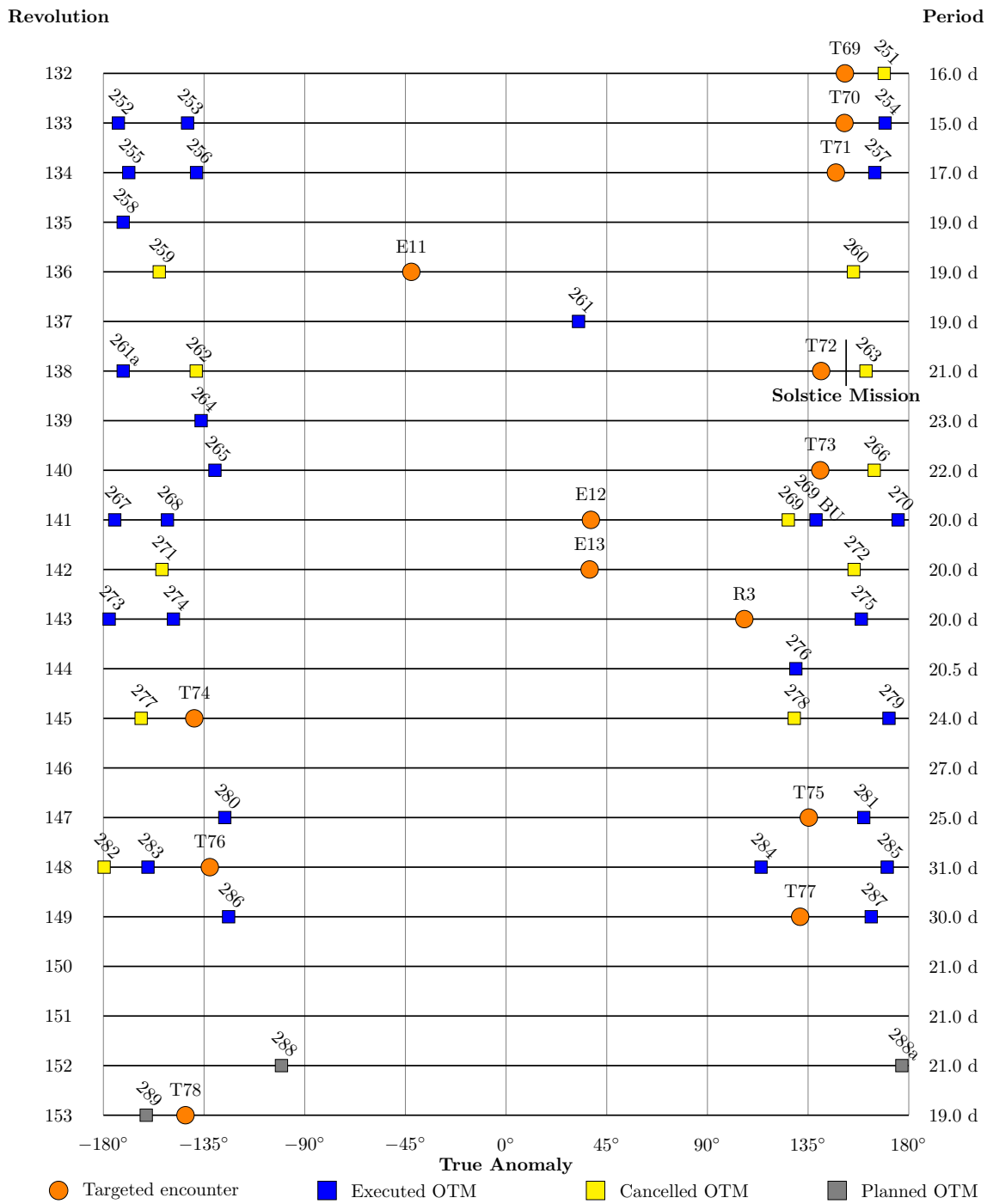



**Figure 2. Titan-69 – Titan-78 Orbital Events**

## MANEUVER EXECUTION

Maneuvers are performed by the Cassini orbiter's bipropellant Main Engine Assembly (MEA) or monopropellant Reaction Control Subsystem (RCS), as noted in Figure 3. The MEA is used for large maneuvers, and the RCS is used for smaller maneuvers, attitude control, and reaction wheel biases. 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, along $\pm$Y-axes, is used to make balanced roll turns about the Z-axis. The other set faces the $-$Z-axis and is used to make unbalanced yaw turns about the Y-axis.

Maneuvers are executed in a turn-and-burn style. The burn orientation is achieved by performing a roll turn followed by a yaw turn (wind turns). The turns are reversed to return to the original attitude (unwind turns). MEA maneuver yaw turns are performed usually with RCS thrusters. Because they are unbalanced for yaw turns, they will impart $\Delta$V, requiring that turn angles be computed so that the turn and burn $\Delta$V sum properly. Turns performed with the Reaction Wheel Assembly (RWA) do not impart $\Delta$V. Nominally, this includes all RCS maneuver turns and MEA maneuver roll turns.

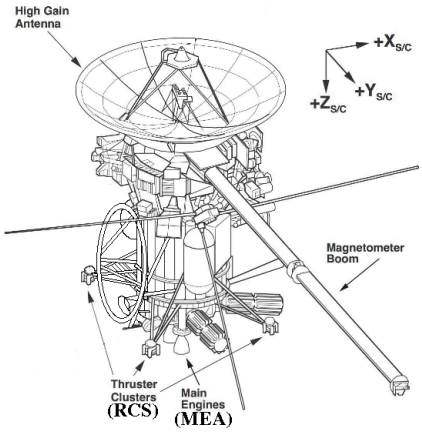



**Figure 3. Cassini Orbiter**

In general, if a maneuver $\Delta$V magnitude is greater than 300 mm/s, MEA is utilized; otherwise, RCS is used. Gates models[15] of the maneuver execution errors for MEA and RCS are implemented for $\Delta$V statistical analysis and the determination of the maneuver delivery accuracies.[4,16] The maneuver execution error models have been updated based on maneuver performance thus far in the Saturnian tour.[17,18]

## NAVIGATION STRATEGY

The nominal navigation strategy employed since the Saturn tour began has been to schedule three propulsive maneuvers between each targeted satellite encounter: a flyby cleanup maneuver and two targeting maneuvers. The first two maneuvers are usually deterministic, whereas the final targeting maneuver is statistical (its execution depends on the accumulation of random error). Cleanup maneuvers are usually performed three days after an encounter; they are used to correct trajectory errors from a previous flyby. They are typically designed with a chained two-impulse optimization strategy, which minimizes the sum of the deterministic maneuvers across several encounters. Besides providing an optimal distribution of the $\Delta$Vs, this optimization strategy helps to control asymptote errors without altering downstream flyby aimpoints after each encounter.[2] The near-apocrone (Saturn apoapsis) maneuver, which is the first maneuver targeted directly to an encounter, is usually performed to "shape" the trajectory in order to achieve the flyby conditions. The approach maneuver, which is the second targeting maneuver, is usually executed three days before an encounter to clean up the errors left by the previous maneuver and to achieve as accurate a flyby as possible. The maneuvers are targeted to the upcoming encounter's three B-plane flyby conditions: the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ and the time of flight (TF). For an explanation of the B-plane, see Reference 19 and the B-Plane Appendix in Reference 4.

Provided that science requirements are met, a maneuver is usually cancelled if it does not guarantee a substantial $\Delta$V savings reflected in the downstream maneuvers, or if a subsequent maneuver

can achieve the aimpoint conditions at a better overall cost. As discussed in the next section, target modifications have been made to save $\Delta$V. Additionally, the time of flight modification strategy[13] has been employed several times to increase a maneuver to an implementable size (above 9 mm/s). A discussion on the maneuver cancellation rationale can be found in Reference 20.

## FLYBY CONDITIONS (TITAN-70 TO TITAN-77)

Table 1 lists the targeted encounter conditions, defined in the 091005 reference trajectory*, and the reconstructed flyby differences for each of the 12 flybys from T70 to T77. Eight of the 12 encounters occurred at the beginning of the Solstice Mission; 6 of these 8 had their flyby targets modified. These modifications in the B-plane conditions relative to the reference trajectory target conditions are indicated in the flyby differences columns of Table 1 by parentheses and italicized font. Only six flybys had been adjusted previously in the Prime and Equinox Missions, three in the time of flight, and three in B-plane coordinates. In just the first nine months of the Solstice Mission, the total number of flyby modifications implemented in the Saturn tour has doubled.

**Table 1. Targeted Encounter History (Titan-70 to Titan-77)**

| Encounter | Flyby Characteristics | | | Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0) | | | | Flyby Differences from Reference Trajectory | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $V_\infty$ ($\frac{km}{s}$) | Period (days) | Inc. (deg) | $\mathbf{B}\cdot\mathbf{R}$ (km) | $\mathbf{B}\cdot\mathbf{T}$ (km) | TCA (ET SCET) | Alt. (km)* | $\Delta\mathbf{B}\cdot\mathbf{R}$ (km) | $\Delta\mathbf{B}\cdot\mathbf{T}$ (km) | $\Delta$TCA (sec) |
| Titan-70 | 5.49 | 16.0 | 19.1 | −3410.81 | −1536.77 | 21-Jun-2010 01:28:49 | 880 | 1.73 | 0.88 | −0.06 |
| Titan-71 | 5.50 | 19.9 | 4.5 | 2172.40 | 3196.98 | 07-Jul-2010 00:23:51 | 1005 | −1.86 | −0.33 | 0.06 |
| Enceladus-11† | 6.84 | 20.1 | 4.6 | 2602.38 | 1030.82 | 13-Aug-2010 22:32:05 | 2552 | −9.34 | 35.94 | −7.23 |
| Titan-72† | 5.53 | 23.8 | 3.0 | −842.63 | 11007.01 | 24-Sep-2010 18:39:47 | 8175 | −0.62 | 2.76 | 0.07 |
| *— Equinox Mission ended on 26-Sep-2010 / Solstice Mission began on 27-Sep-2010 —* | | | | | | | | | | |
| Titan-73‡ | 5.44 | 20.6 | 0.0 | 8682.89 | −6413.18 | 11-Nov-2010 13:38:07 | 7921 | 5.64 *(+4.5)* | −0.77 *(+1.5)* | 0.002 |
| Enceladus-12 | 6.26 | 20.6 | 0.1 | −164.28 | −248.01 | 30-Nov-2010 11:55:05 | 50 | −0.77 | 3.18 | 0.60 |
| Enceladus-13†,‡ | 6.22 | 20.7 | 0.1 | −297.40 | 7.00 | 21-Dec-2010 01:09:32 | 50 | −0.47 | 0.91 | 0.95 *(+0.7)* |
| Rhea-3‡ | 8.02 | 20.4 | 0.3 | 826.35 | 158.37 | 11-Jan-2011 04:54:31 | 75 | −4.59 *(−5.0)* | −5.62 *(−5.0)* | 0.005 |
| Titan-74† | 5.49 | 28.0 | 0.4 | 2957.82 | −5806.42 | 18-Feb-2011 16:05:17 | 3651 | −2.12 | −1.51 | 0.23 |
| Titan-75‡ | 5.42 | 23.4 | 0.4 | 5026.68 | −11912.22 | 19-Apr-2011 05:01:45 | 10053 | −12.27 *(−12.0)* | −5.21 *(−5.0)* | −0.04 |
| Titan-76‡ | 5.51 | 39.0 | 0.4 | 2128.65 | −4228.96 | 08-May-2011 22:54:51 | 1873 | −0.34 | 0.39 | −0.51 *(−0.4)* |
| Titan-77‡ | 5.49 | 21.7 | 0.4 | 1922.11 | −3758.27 | 20-Jun-2011 18:33:07 | 1359 | −0.07 | −0.18 | −0.42 *(−0.4)* |

* Flyby altitude was not explicitly targeted in maneuver designs. Reported altitude is relative to a sphere.
† Flyby differences from reference trajectory target conditions may appear large due to cancelled maneuvers.
‡ Target condition(s) changed via maneuver. Flyby B-plane and time of flight shifts relative to the reference trajectory target conditions are indicated in parentheses and italicized in the flyby differences columns.

*The reference trajectory provides predetermined maneuver locations and flyby targets according to science sequence planning and objectives. 091005 is the release date of the reference trajectory update (October 5, 2009).

The increased frequency of modified targeted encounters can be attributed to a shift in the Project's rationale for executing maneuvers in the Solstice Mission. Navigation recommends slight target refinements, as opposed to redesigns, when they result in a propellant savings, even if small, while satisfying science requirements. Prior to the Solstice Mission, small $\Delta$V savings from slight flyby modifications would usually not justify another spacecraft maneuver cycle, although the opportunities to make such adjustments were just as frequent as in the current portion of the Saturn tour. For example, of the six flyby modifications, four were made to save downstream $\Delta$V ranging as small as 0.075 to 0.2 m/s. These types of savings usually translate to preserving RCS hydrazine, at roughly 1 gram of hydrazine per mm/s of $\Delta$V.

## MANEUVER HISTORY (OTM-251 THROUGH OTM-287)

The maneuver design and reconstruction history from OTM-251 to OTM-287 is presented in Table 2, where maneuvers are grouped and separated by the targeted encounters. The table lists the maneuver epoch; the true anomaly; the central angle; the design and reconstructed $\Delta$Vs (magnitude, right ascension, and declination); and the engine type (MEA or RCS). True anomaly as reported is for an osculating ellipse with respect to Saturn, measured from apocrone to apocrone; it indicates where the spacecraft was in the orbit at the time of the maneuver (e.g., at a value of 180°, the spacecraft was at apocrone). Central angle is defined as the angle $\angle$(maneuver)-Saturn-(target), measured from the maneuver to the target and counting multiple revolutions. The encounter rows contain the encounter name, the time of closest approach, the flyby altitude, the $\Delta$V imparted to the spacecraft from the encounter (flyby $\Delta$V), whether the flyby is inbound or outbound*, the days to the next encounter, and, if the target was modified, the change in the aimpoint or time of flight.

Out of 38 opportunity windows, 27 maneuvers were performed; 8 of those were implemented with MEA while 19 used RCS. Since the Solstice Mission began, only 2 of the 18 maneuvers performed have used the main engine. The backup maneuver window for OTM-269 was performed, indicated as OTM-269 BU (backup). There are backup maneuvers scheduled for each maneuver window, usually 24 hours after the prime maneuver locations. Although not yet accomplished at the time of this paper, T78 is included to provide context for OTM-287, which was executed on June 24, 2011 to target T78. Spacing between maneuvers was often only a week or less, as evidenced in Table 2. Designing maneuvers given short turn-around times has been common in Cassini maneuver operations since the Saturn tour began in July 2004.[2]

The Saturn tour takes advantage of the substantial gravity assists provided by each Titan encounter, with closer flybys imparting larger $\Delta$Vs to the spacecraft. For example, a Titan flyby at an altitude of 1000 km and a $V_\infty$ of 5.5 km/s supplies an equivalent $\Delta$V of about 840 m/s to Cassini. With the large flyby $\Delta$Vs imparted by Titan (see encounter rows in Table 2), the maneuver $\Delta$Vs performed by Cassini were quite small in comparison. In fact, following the large Saturn Orbit Insertion (SOI) maneuver on July 1, 2004,[7] Cassini has executed a cumulative $\Delta$V of just under 1 km/s, only 2% of the $\sim$50 km/s imparted to date by the Titan flybys.

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

## Table 2. Maneuver History (OTMs 251–287)

| Maneuver | Orbit Location | Maneuver Time (UTC SCET) | True Anomaly (deg) | Central Angle (deg) | Total Design $\Delta\mathbf{V}^*$ Mag. (m/s) | RA (deg) | DEC (deg) | Total Reconstructed $\Delta\mathbf{V}^*$ Mag. (m/s) | RA (deg) | DEC (deg) | Burn Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Titan-69 (T69): 05-Jun-2010 02:27:33 ET SCET, Alt. = 2044 km, Flyby $\Delta$V = 664.9 m/s, Outbound, 16.0 days to T70* | | | | | | | | | | | |
| OTM-251 | T69+3d | 08-Jun-2010 02:43 | 169.02 | 341.69 | ..... *CANCELLED* ..... | | | | | | |
| OTM-252 | ∼apo | 13-Jun-2010 08:42 | −173.29 | 324.01 | 1.239 | 12.10 | 71.67 | 1.242 | 11.93 | 71.47 | MEA |
| OTM-253 | T70−3d | 18-Jun-2010 02:11 | −142.33 | 293.09 | 0.025 | 164.91 | 10.45 | 0.025 | 164.99 | 10.36 | RCS |
| *Titan-70 (T70): 21-Jun-2010 01:28:49 ET SCET, Alt. = 880 km, Flyby $\Delta$V = 871.5 m/s, Outbound, 15.9 days to T71* | | | | | | | | | | | |
| OTM-254 | T70+3d | 24-Jun-2010 07:56 | 169.42 | 339.25 | 0.874 | 57.36 | 50.98 | 0.870 | 57.27 | 50.84 | MEA |
| OTM-255 | ∼apo | 30-Jun-2010 07:40 | −168.61 | 317.28 | 6.258 | 57.63 | 58.68 | 6.255 | 57.55 | 58.60 | MEA |
| OTM-256 | T71−3d | 04-Jul-2010 01:09 | −138.32 | 287.00 | 0.022 | 181.96 | 11.59 | 0.023 | 181.87 | 11.42 | RCS |
| *Titan-71 (T71): 07-Jul-2010 00:23:51 ET SCET, Alt. = 1005 km, Flyby $\Delta$V = 841.9 m/s, Outbound, 37.9 days to E11* | | | | | | | | | | | |
| OTM-257 | T71+3d | 10-Jul-2010 06:53 | 164.82 | 512.87 | 0.838 | 296.89 | −16.34 | 0.832 | 297.04 | −16.26 | MEA |
| OTM-258 | ∼apo | 18-Jul-2010 06:37 | −171.12 | 488.83 | 6.770 | 197.07 | −87.98 | 6.765 | 197.87 | −88.07 | MEA |
| OTM-259 | E11-3d | 10-Aug-2010 22:35 | −155.06 | 112.58 | ..... *CANCELLED* ..... | | | | | | |
| *Enceladus-11 (E11): 13-Aug-2010 22:32:05 ET SCET, Alt. = 2552 km, Flyby $\Delta$V = 0.8 m/s, Inbound, 41.8 days to T72* | | | | | | | | | | | |
| OTM-260 | E11+3d | 17-Aug-2010 04:49 | 155.25 | 708.20 | ..... *CANCELLED* ..... | | | | | | |
| OTM-261 | ∼peri | 03-Sep-2010 03:33 | 32.64 | 471.03 | 2.439 | 222.63 | 21.81 | 2.438 | 222.78 | 22.05 | MEA |
| OTM-261a | ∼apo | 16-Sep-2010 02:47 | −171.15 | 314.40 | 0.176 | 307.36 | 4.64 | 0.175 | 307.02 | 5.07 | RCS |
| OTM-262 | T72-3d | 21-Sep-2010 12:47 | −138.48 | 281.77 | ..... *CANCELLED* ..... | | | | | | |
| *Titan-72 (T72): 24-Sep-2010 18:39:47 ET SCET, Alt. = 8175 km, Flyby $\Delta$V = 293.8 m/s, Outbound, 47.8 days to T73* | | | | | | | | | | | |
| *— Equinox Mission ended on 26-Sep-2010 / Solstice Mission began on 27-Sep-2010 —* | | | | | | | | | | | |
| OTM-263 | T72+3d | 28-Sep-2010 02:02 | 160.88 | 696.79 | ..... *CANCELLED* ..... | | | | | | |
| OTM-264 | ∼peri | 15-Oct-2010 01:02 | −136.37 | 634.31 | 0.182 | 191.18 | 7.13 | 0.177 | 190.64 | 6.95 | RCS |
| OTM-265 | T73-3d | 08-Nov-2010 09:49 | −130.11 | 268.01 | 0.172 | 182.15 | 7.88 | 0.167 | 181.41 | 8.10 | RCS |
| *Titan-73 (T73): 11-Nov-2010 13:38:07 ET SCET, Alt. = 7923 km, Flyby $\Delta$V = 305.4 m/s, Outbound, 18.9 days to E12, $\Delta\mathbf{B}$= [+4.5, +1.5] km* | | | | | | | | | | | |
| OTM-266 | T73+3d | 14-Nov-2010 23:19 | 164.56 | 233.49 | ..... *CANCELLED* ..... | | | | | | |
| OTM-267 | ∼apo | 21-Nov-2010 23:05 | −174.91 | 212.98 | 2.250 | 230.92 | −73.61 | 2.249 | 231.78 | −73.81 | MEA |
| OTM-268 | E12-3d | 27-Nov-2010 16:20 | −151.37 | 189.45 | 0.065 | 149.20 | 29.39 | 0.065 | 149.24 | 29.04 | RCS |
| *Enceladus-12 (E12): 30-Nov-2010 11:55:05 ET SCET, Alt. = 50 km, Flyby $\Delta$V = 7.7 m/s, Outbound, 20.6 days to E13* | | | | | | | | | | | |
| OTM-269 | E12+1d | 01-Dec-2010 08:36 | 126.11 | 271.33 | ..... *DELAYED* ..... | | | | | | |
| OTM-269 BU | E12+1d | 01-Dec-2010 22:21 | 138.51 | 258.93 | 0.163 | 234.45 | −20.78 | 0.162 | 234.15 | −20.48 | RCS |
| OTM-270 | ∼apo | 08-Dec-2010 22:07 | 175.24 | 222.23 | 0.016 | 73.14 | −10.41 | 0.016 | 73.18 | −10.53 | RCS |
| OTM-271 | E13-3d | 17-Dec-2010 21:23 | −153.85 | 191.33 | ..... *CANCELLED* ..... | | | | | | |
| *Enceladus-13 (E13): 21-Dec-2010 01:09:32.7 ET SCET, Alt. = 50 km, Flyby $\Delta$V = 7.8 m/s, Outbound, 21.2 days to R3, $\Delta\mathbf{TF}$= +0.7 sec* | | | | | | | | | | | |
| OTM-272 | E13+3d | 24-Dec-2010 07:09 | 155.57 | 311.09 | ..... *CANCELLED* ..... | | | | | | |
| OTM-273 | ∼apo | 01-Jan-2011 06:40 | −177.43 | 284.07 | 0.210 | 113.55 | −40.33 | 0.208 | 114.07 | −40.71 | RCS |
| OTM-274 | R3-3d | 08-Jan-2011 06:26 | −148.69 | 255.34 | 0.034 | 130.33 | −72.35 | 0.034 | 131.15 | −72.38 | RCS |
| *Rhea-3 (R3): 11-Jan-2011 04:54:31 ET SCET, Alt. = 69 km, Flyby $\Delta$V = 45.9 m/s, Outbound, 38.5 days to T74, $\Delta\mathbf{B}$= [−5.0, −5.0] km* | | | | | | | | | | | |
| OTM-275 | R3+3d | 14-Jan-2011 13:27 | 158.81 | 417.86 | 2.766 | 83.09 | 71.36 | 2.763 | 82.80 | 71.22 | MEA |
| OTM-276 | ∼peri | 01-Feb-2011 04:44 | 129.52 | 86.98 | 0.020 | 185.65 | 65.31 | 0.021 | 185.47 | 65.09 | RCS |
| OTM-277 | T74-3d | 15-Feb-2011 17:46 | −163.14 | 19.64 | ..... *CANCELLED* ..... | | | | | | |
| *Titan-74 (T74): 18-Feb-2011 16:05:17 ET SCET, Alt. = 3651 km, Flyby $\Delta$V = 501.0 m/s, Inbound, 59.5 days to T75* | | | | | | | | | | | |
| OTM-278 | T74+3d | 22-Feb-2011 03:31 | 128.78 | 723.99 | ..... *CANCELLED* ..... | | | | | | |
| OTM-279 | ∼apo | 02-Mar-2011 10:17 | 171.16 | 681.61 | 0.100 | 166.68 | 64.56 | 0.100 | 166.36 | 64.12 | RCS |
| OTM-280 | T75-3d | 15-Apr-2011 23:48 | −125.70 | 258.41 | 0.020 | 347.15 | 2.47 | 0.022 | 347.00 | 2.48 | RCS |
| *Titan-75 (T75): 19-Apr-2011 05:01:45 ET SCET, Alt. = 10053 km, Flyby $\Delta$V = 256.0 m/s, Outbound, 19.8 days to T76, $\Delta\mathbf{B}$= [−12.0, −5.0] km* | | | | | | | | | | | |
| OTM-281 | T75+3d | 22-Apr-2011 06:48 | 159.88 | 61.30 | 0.043 | 294.13 | 43.12 | 0.042 | 293.66 | 43.41 | RCS |
| OTM-282 | ∼apo | 29-Apr-2011 06:18 | −179.67 | 40.86 | ..... *CANCELLED* ..... | | | | | | |
| OTM-283 | T76-3d | 05-May-2011 22:17 | −160.08 | 21.27 | 0.014 | 314.90 | 3.71 | 0.015 | 314.88 | 3.84 | RCS |
| *Titan-76 (T76): 08-May-2011 22:54:50.6 ET SCET, Alt. = 1873 km, Flyby $\Delta$V = 686.7 m/s, Inbound, 42.8 days to T77, $\Delta\mathbf{TF}$= -0.4 sec* | | | | | | | | | | | |
| OTM-284 | T76+3d | 12-May-2011 05:32 | 113.93 | 368.77 | 0.121 | 173.04 | −8.03 | 0.120 | 173.48 | −7.99 | RCS |
| OTM-285 | ∼apo | 24-May-2011 04:46 | 170.37 | 312.31 | 0.037 | 8.83 | 6.11 | 0.037 | 8.93 | 6.45 | RCS |
| OTM-286 | T77-3d | 17-Jun-2011 02:57 | −124.01 | 246.70 | 0.015 | 314.03 | −3.39 | 0.016 | 313.86 | −3.34 | RCS |
| *Titan-77 (T77): 20-Jun-2011 18:33:06.6 ET SCET, Alt. = 1359 km, Flyby $\Delta$V = 773.2 m/s, Outbound, 83.3 days to T78, $\Delta\mathbf{TF}$= -0.4 sec* | | | | | | | | | | | |
| OTM-287 | T77+3d | 24-Jun-2011 08:42 | 163.23 | 1137.86 | 0.146 | 206.06 | 3.20 | 0.145 | 205.66 | 3.39 | RCS |
| *— OTM-288 (22-Aug-2011 15:04), OTM-288a (01-Sep-2011 22:03), and OTM-289 (09-Sep-2011 03:48) if needed —* | | | | | | | | | | | |
| *Titan-78 (T78): 12-Sep-2011 02:51:12 ET SCET, Alt. = 5821 km, Flyby $\Delta$V = 368.9 m/s, Inbound* | | | | | | | | | | | |

* 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 dead-band tightening/limit-cycling for RCS burns. Expressed in Earth Mean Equator & Equinox of J2000.0 coordinates (EME2000).

Table 3 lists the $\Delta$V characteristics of each maneuver covered in the scope of this paper, including the maneuver location (true anomaly and central angle), the $\Delta$V magnitude, and the roll and yaw turn angles to orient the maneuver burns. Each maneuver has two designs, one at the prime window and one at the backup window. Backup maneuver windows are usually scheduled 24 hours after the prime maneuver windows. Data from the maneuver design that was implemented on the spacecraft are shaded in gray. Data from the 'Cancel OTM Cost' that was realized in operations are also shaded in gray.

**Table 3. Maneuver Window Characteristics (OTMs 251–287)**

| | Prime Maneuver Window | | | | | Backup Maneuver Window | | | | | Cancel | Down- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OTM | True Anom. (deg) | Central Angle (deg) | $\Delta$V Mag. (m/s) | Roll Angle (deg) | Yaw Angle (deg) | True Anom. (deg) | Central Angle (deg) | $\Delta$V Mag. (m/s) | Roll Angle (deg) | Yaw Angle (deg) | OTM Cost* (m/s) | stream OTM Length |
| 251 | 169.02 | 341.69 | 0.119 | −81.45 | −68.09 | 172.8 | 338.0 | 0.181 | 69.84 | −68.48 | 0.029 | 261 |
| 252 | −173.29 | 324.01 | 1.239 | 14.51 | −72.65 | −169.6 | 320.3 | 1.221 | 11.76 | −70.94 | — | — |
| 253 | −142.33 | 293.09 | 0.025 | −124.08 | −164.10 | −122.7 | 273.5 | 0.037 | 145.85 | −169.01 | 2.881 | 264 |
| 254 | 169.42 | 339.25 | 0.874 | 37.44 | −70.48 | 174.9 | 333.8 | 1.065 | 39.26 | −73.38 | −0.016 | 264 |
| 255 | −168.61 | 317.28 | 6.258 | 25.45 | −73.82 | −163.9 | 312.6 | 6.349 | 21.55 | −72.01 | — | — |
| 256 | −138.32 | 287.00 | 0.022 | 161.65 | −170.76 | −113.2 | 262.0 | 0.031 | 127.98 | −157.12 | 1.045 | 264 |
| 257 | 164.82 | 512.87 | 0.838 | 85.36 | −60.93 | 168.5 | 509.2 | 1.077 | −104.27 | −63.55 | 8.029 | 264 |
| 258 | −171.12 | 488.83 | 6.770 | 24.35 | −87.07 | −167.8 | 485.6 | 6.824 | 10.64 | −86.47 | — | — |
| 259 | −155.06 | 112.58 | 0.098 | 106.45 | −131.68 | −146.9 | 104.4 | 0.178 | 104.42 | −135.51 | −0.111 | 273 |
| 260 | 155.25 | 708.20 | 0.058 | 161.91 | −118.27 | 160.8 | 702.7 | 0.111 | 176.05 | −113.52 | 0.010 | 273 |
| 261 | 32.64 | 471.03 | 2.439 | 111.70 | −134.97 | 130.6 | 372.7 | 5.742 | 80.74 | −122.09 | — | — |
| 261a | −171.15 | 314.40 | 0.176 | −80.72 | −58.79 | −167.8 | 311.1 | 0.216 | −80.94 | −56.12 | 4.335 | 273 |
| 262 | −138.48 | 281.77 | 0.015 | 72.38 | −25.08 | −125.3 | 268.6 | 0.015 | 29.55 | −12.73 | −0.122 | 273 |
| 263 | 160.88 | 696.79 | 0.057 | −135.71 | −151.61 | 162.5 | 695.1 | 0.051 | 112.83 | −155.33 | 0.004 | 273 |
| 264 | −136.37 | 634.31 | 0.182 | −168.33 | −171.00 | −111.1 | 609.2 | 0.221 | 129.69 | −150.26 | — | — |
| 265 | −130.11 | 268.01 | 0.172 | −137.27 | −165.84 | −112.7 | 250.6 | 0.238 | 152.86 | −165.87 | 0.911 | 276 |
| 266 | 164.56 | 233.49 | 0.071 | 82.69 | −105.49 | 168.2 | 229.9 | 0.056 | 67.28 | −105.02 | 0.003 | 276 |
| 267 | −174.91 | 212.98 | 2.250 | 15.76 | −103.63 | −172.1 | 210.1 | 2.510 | 15.74 | −102.67 | — | — |
| 268 | −151.37 | 189.45 | 0.065 | 60.24 | −126.11 | −141.2 | 179.3 | 0.120 | 122.20 | −142.17 | −0.041 | 279 |
| 269 | 126.11 | 271.33 | 0.167 | −120.36 | −145.52 | 138.51 | 258.93 | 0.163 | −94.40 | −137.26 | 0.441 | 279 |
| 270 | 175.24 | 222.23 | 0.016 | 20.36 | −59.92 | 177.9 | 219.5 | 0.017 | 18.54 | −65.60 | 1.187 | 279 |
| 271 | −153.85 | 191.33 | 0.026 | −170.92 | −90.28 | −145.4 | 182.9 | 0.039 | −172.53 | −78.03 | −0.056 | 282 |
| 272 | 155.57 | 311.09 | 0.051 | 42.01 | −141.98 | 160.8 | 305.8 | 0.031 | 68.13 | −138.93 | 0.011 | 282 |
| 273 | −177.43 | 284.07 | 0.210 | 136.68 | −98.48 | −174.7 | 281.3 | 0.237 | 131.63 | −100.71 | — | — |
| 274 | −148.69 | 255.34 | 0.034 | −19.10 | −101.24 | −136.4 | 243.1 | 0.052 | −16.03 | −105.64 | 0.196 | 285 |
| 275 | 158.81 | 417.86 | 2.766 | −62.25 | −75.89 | 163.43 | 413.25 | 2.250 | −55.09 | −74.99 | — | — |
| 276 | 129.52 | 86.98 | 0.020 | 27.29 | −109.88 | 145.70 | 70.78 | 0.017 | 17.11 | −122.98 | 6.346 | 288 |
| 277 | −163.14 | 19.64 | 0.017 | −111.79 | −34.37 | −158.45 | 14.95 | 0.027 | −109.55 | −36.89 | 0.092 | 288 |
| 278 | 128.78 | 723.99 | 0.081 | −177.84 | −87.17 | 141.55 | 711.22 | 0.077 | 178.60 | −88.93 | 0.018 | 288 |
| 279 | 171.16 | 681.61 | 0.100 | 15.00 | −108.33 | 173.43 | 679.34 | 0.094 | 17.80 | −107.87 | — | — |
| 280 | −125.70 | 258.41 | 0.020 | 87.37 | −25.63 | −79.91 | 212.67 | 0.036 | −117.42 | −15.69 | 0.077 | 288 |
| 281 | 159.88 | 61.30 | 0.043 | −131.57 | −79.77 | 163.79 | 57.39 | 0.045 | −136.71 | −83.64 | 0.060 | 291 |
| 282 | −179.67 | 40.86 | 0.015 | 174.02 | −23.02 | −177.22 | 38.41 | 0.016 | 175.45 | −25.22 | 1.124 | 291 |
| 283 | −160.08 | 21.27 | 0.014 | −171.88 | −56.53 | −155.31 | 16.50 | 0.013 | −165.90 | −81.27 | 0.831 | 291 |
| 284 | 113.93 | 368.77 | 0.121 | 132.19 | −160.86 | 130.84 | 351.85 | 0.139 | 109.03 | −176.25 | 0.379 | 291 |
| 285 | 170.37 | 312.31 | 0.037 | −21.80 | −4.69 | 172.02 | 310.66 | 0.035 | 2.46 | −4.29 | 14.908 | 297 |
| 286 | −124.01 | 246.70 | 0.015 | 125.74 | −56.59 | −97.00 | 219.71 | 0.017 | 110.37 | −32.00 | 0.086 | 297 |
| 287 | 163.23 | 1137.86 | 0.146 | 114.37 | −163.64 | 166.93 | 1134.15 | 0.181 | 112.69 | −159.11 | 4.202 | 297 |

* Cancel OTM $\Delta$V cost is the downstream deterministic $\Delta$V cost of cancelling the listed maneuver. If cancelled, shaded in gray.

† Downstream OTM length is the last OTM included in the downstream deterministic maneuvers, including the current maneuver. This maneuver length was used to determine the cancel OTM $\Delta$V cost.

## MANEUVER OPERATIONS THROUGH FINAL MONTHS OF EQUINOX MISSION

The following sections provide in-depth discussions of the maneuver decision process during operations through the end of the Equinox Mission on September 26, 2010. The last four months of the Equinox Mission, June – September 2010, were used primarily to set up the first equatorial phase of the Solstice Mission.[1] This time period was distinguished by several events, the lowest Titan flyby to date and for the rest of the mission, at 880 km; and OTM-261 BU, the first of two problematic backup maneuvers.

### Targeting Titan-70

OTMs 251, 252, and 253 were designed to target T70, the lowest Titan flyby (880 km) planned for the entire Saturn tour. Prior to this encounter, the lowest Titan flyby altitude occurred during the Prime Mission with T16 at 950 km on July 22, 2006.[10]

Because OTM-250 produced a 1-$\sigma$ error of only about 1 km in the prior T69 flyby, OTM-251, the cleanup maneuver prior to T70, became a good candidate for cancellation. Cancelling OTM-251 would cause OTM-254 to increase perhaps so as to require the MEA. Also, OTM-251 cancellation presented a negligible downstream $\Delta$V penalty of $\sim$30 mm/s and a cleaner orbit determination (OD) solution for OTM-252. OTM-251 was cancelled in favor of OTM-252, which was targeted directly to T70.

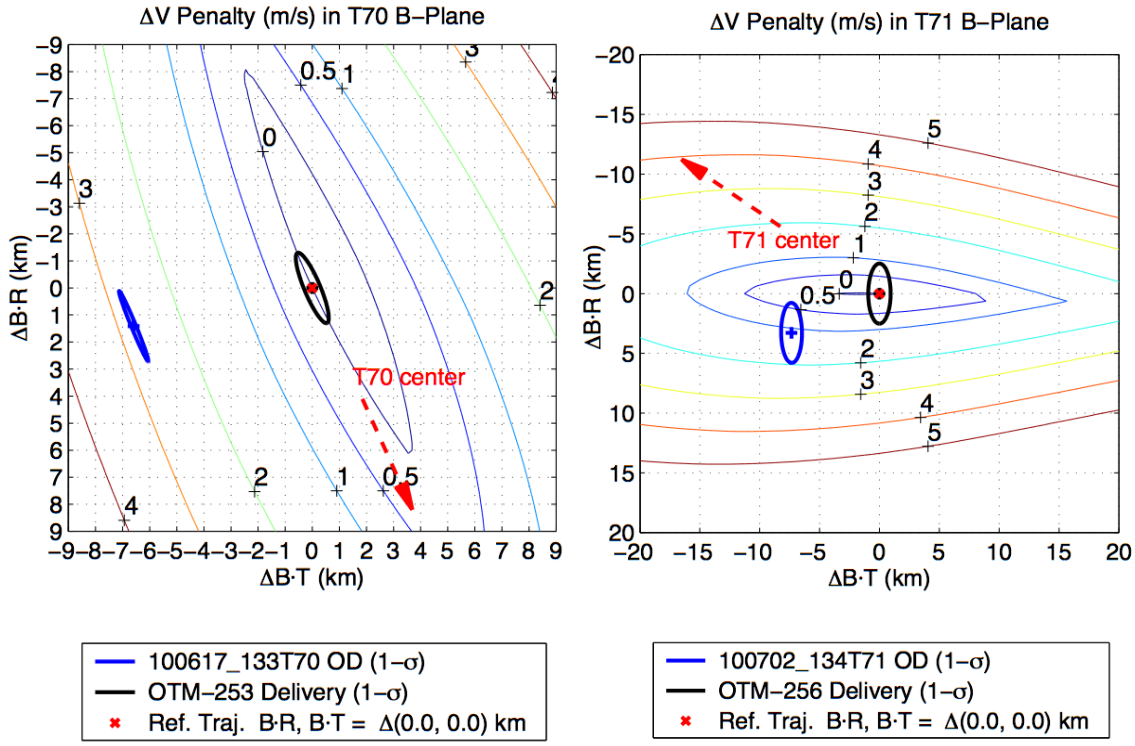
The ramifications of performing or cancelling a maneuver are often explored via contour plots of downstream $\Delta$V cost vs. B-plane aimpoint miss. Figure 4 showcases two of these contour plots, one for the T70 B-plane and one for the T71 B-plane. For an explanation of how each contour plot was produced, see Reference 21. Steep contours of up to 2 m/s within the 1-$\sigma$ predicted OTM-252 maneuver delivery ellipse were seen. So it was no surprise that a 7 km flyby miss as a result of OTM-252's performance would produce nearly a 3 m/s downstream $\Delta$V cost, as seen with the blue OD ellipse in the $\Delta$V cost contour plot in Figure 4(a). That necessitated OTM-253's execution, or OTM-254 would have grown to 3.5 m/s. A $-0.2$ m/s region was also observed in the contour plot. This was still deemed too small a savings to justify an aimpoint adjustment. Soon after the start of the Solstice Mission, a saving of 0.2 m/s would be considered non-trivial.

### Inclination Reduction (Titan-71, Enceladus-11, and Titan-72)

The final months of the Equinox Mission consisted of resonant Titan-to-Titan transfers, T71 and T72, that decreased the orbit inclination from the initial 19.1° to 3.0° in order to set up the first equatorial phase of the Solstice Mission. These two flybys and E11 were targeted by OTMs 254–262.

*Cleanup Maneuvers Optimized With Large Apocrone Maneuvers* OTM-254 grew to $\sim$0.9 m/s following the T70 flyby. Even with this size, the downstream $\Delta$V cost of folding OTM-254 into OTM-255 to target T71 directly was virtually the same. In fact, cancelling OTM-254 provided a predicted savings of 16 mm/s. Although there was no real cost to cancel, the Project decided to perform both OTM-254 and OTM-255 in an optimization chain in order to maintain the spacecraft trajectory closer to the reference trajectory. The final approach maneuver, OTM-256, was performed to avoid a 1 m/s downstream cost that OTM-255's 8 km error in the T71 B-plane would have produced if left uncorrected. Like OTM-254, OTM-257 was designed in an optimization chain with its apocrone maneuver, OTM-258, the targeting maneuver to E11, and downstream maneuvers. Cancelling OTM-257 in favor of OTM-258 was not a viable option as the $\Delta$V cost was a prohibitive

8 m/s. The design of OTM-257 increased from a 0.2 m/s RCS maneuver to a 0.8 m/s MEA maneuver after the T71 flyby. The $\Delta$V cost contour plot at T71, see Figure 4(b), accurately predicted that a 2 km T71 miss would increase the downstream $\Delta$V cost in the range of 0.5 to 1 m/s, a cost that was reflected mostly in the size of OTM-257.




(a) T70 Cost Contours at Time of OTM-253

(b) T71 Cost Contours at Time of OTM-256

**Figure 4. T70/T71 B-Plane Shifts vs. $\Delta$V Contours**

The final opportunity to modify the E11 aimpoint was through the implementation of OTM-259. Given the high E11 flyby altitude of 2552 km which yielded a flyby $\Delta$V of only 1 m/s, there was a predicted savings of over 0.1 m/s by cancelling OTM-259, mainly attributable to OTM-259's $\Delta$V. Cancelling OTM-259 would leave a $\sim$9 km error in $\mathbf{B} \cdot \mathbf{R}$ and a $\sim$36 km error in $\mathbf{B} \cdot \mathbf{T}$ (see Table 1), but this error was mainly along the tangential direction, preserving the desired Enceladus altitude. OTM-259 was cancelled for these reasons and to save the equivalent 100 grams of hydrazine.

*Four-Maneuver Arc from Enceladus-11 to Titan-72* An exception to the nominal navigation targeting strategy, four maneuver opportunities were planned to target the T72 aimpoint. This included OTMs 260, 261, 261a, and 262. OTM-261a was added to lessen the risk of OTM-262 growing to a MEA burn as it would be the final T72 approach maneuver opportunity.

*OTM-261 Backup Complications* OTM-260, the cleanup maneuver following E11, was cancelled because there was only a negligible cost of 10 mm/s and OTM-261 does the majority of the shaping to achieve T72. OTM-261, at a true anomaly of 33° with a central angle change of 471°, yielded a 2.4 m/s $\Delta$V. The placement of OTM-261 BU at a true anomaly of 131° with a central angle change of 373° decreased the capability of the backup maneuver with respect to the T72 B-plane such that the $\Delta$V size would increase to 11.2 m/s. OTM-261a prior to the final approach maneuver OTM-262 provided another backup maneuver. The maneuver strategy of optimizing OTM-261 BU

in a downstream chain with OTM-261a was chosen, as first reported in Reference 22. This strategy reduced the size of OTM-261 BU to 5.7 m/s, with a combined $\Delta$V cost of 6.4 m/s with OTM-261a. OTM-261 was in fact executed successfully, but with a large pointing error that necessitated the execution of OTM-261a to eliminate a 4.3 m/s downstream $\Delta$V cost. The use of OTM-261a instead of OTM-262, which would have been a sizeable MEA burn of 0.73 m/s, also validated the inclusion of OTM-261a to avoid a MEA OTM-262.

Wrapping up maneuver operations in the Equinox Mission, an implementable OTM-262 would have required a T72 time-of-flight shift of 0.3 second to correct a 3 km error left by the execution of OTM-261a. However, skipping OTM-262 would save a predicted 0.12 m/s downstream, keep the spacecraft trajectory closer to the reference, keep OTM-263 small, and not impact science due to the high 8175 km Titan flyby. Because of these reasons, the Project cancelled OTM-262.

## MANEUVER OPERATIONS IN FIRST YEAR OF SOLSTICE MISSION

This section provides the details of the day-to-day maneuver operations through the first nine months of the Solstice Mission. This second extended mission officially began on September 27, 2010, three days after the T72 flyby. In the first nine months of this extended mission, six of the eight targeted flybys were accomplished with aimpoint adjustments from the 091005 reference trajectory.[23] Whereas the six years of the Prime and Equinox Missions had six altered targeted flyby aimpoints, after the first year of the Solstice Mission this number had doubled to 12. There were also several instances where the predicted downstream $\Delta$V costs were the same whether by performing only the cleanup or the apocrone maneuver to target the flyby, or by optimizing both maneuvers in an optimization chain.

### Beginning the Equatorial Phase

OTMs 263, 264, and 265 were designed to target T73. The cost of performing OTM-263, either optimized with OTM-264 or targeting T73 alone, was similar to that of folding it into OTM-264. One disadvantage of performing OTM-263 alone was that OTM-266 would increase to a nearly MEA size of 0.27 m/s given a perfect T73 flyby. Ultimately, OTM-263 was cancelled because there was no compelling reason to perform it. OTM-264 then became a must-do maneuver because a B-plane correction of over 400 km was still necessary. The predicted 1-$\sigma$ error in the execution of OTM-264 could yield a cost of 0.5 to 1 m/s, as seen in a $\Delta$V cost vs. T73 aimpoint contour plot, increasing the likelihood that OTM-265 would be needed. An unexpected event, explained next, would further indicate its necessity.

### Spacecraft Safing Prior to Titan-73

The Cassini orbiter went into safe mode on November 2, 2010 at approximately 3:57 PM PST. This was the second time that the spacecraft entered the precautionary standby mode since entering a Saturnian orbit in 2004, the first time being in 2007. Safing was caused by a Command and Data Subsystem (CDS) "non-maskable interrupt error" fault where the command was sent to the spacecraft correctly, but was received incorrectly. The safing imparted 18.3 mm/s to the spacecraft due to thruster activity, spending $\sim$39 grams of hydrazine, and moved the spacecraft trajectory away from the T73 aimpoint. The entry into safe mode automatically terminated the background sequence and put the spacecraft attitude under RCS control.

*Titan-73 Flyby Aimpoint Change* OTM-265, the first maneuver following the safing event, was executed to avoid both a predicted 0.9 m/s cancellation cost and the possibility of OTMs 266 and 273 requiring the MEA. The T73 aimpoint was also altered by +4.5 km in $\mathbf{B} \cdot \mathbf{R}$ and +1.5 km in $\mathbf{B} \cdot \mathbf{T}$ to save an additional 0.1 m/s downstream. This was the smallest $\Delta$V savings to date to justify aimpoint shifts, and established a precedent for subsequent decisions. Because the spacecraft was under RCS control, both roll and yaw turns (wind and unwind) were performed on RCS instead of RWA. Roll turns on RCS are balanced, but yaw turns on RCS are not. Because of this, the wind and unwind yaw turns imparted small $\Delta$Vs, estimated to be $\sim$1 mm/s.

**Three Close Icy Satellite Flybys: Enceladus-12, Enceladus-13, and Rhea-3**

Now in a Saturn equatorial orbit, the spacecraft entered into the first of a series of close icy satellite flybys. Cassini made two consecutive 50 km flybys of Enceladus, E12 and E13, and a close flyby of Rhea at 75 km, R3.

*Returning to RWA Control* OTMs 266, 267, and 268 were designed to target E12.The T73 flyby left the orbiter in an Enceladus impact trajectory. OTM-266 was cancelled knowing that one of two maneuver opportunities, OTMs 267 or 268, would take Cassini off its impacting trajectory to Enceladus. OTM-267, the first MEA maneuver of the Solstice Mission, was executed to remove the nearly 50% chance of impact. This maneuver also marked the return to the background sequence following the unwind roll on RWA control.

*OTM-268 Complications* OTM-268 seemed to be a return to normal operations following the successful transition back to RWA control and the background sequence, but it turned out to have problems of its own. Whereas the prime maneuver design was 65 mm/s, the backup maneuver was nearly 10 times larger to target the reference trajectory E12 aimpoint. The nearly 180° central angle of the backup maneuver location, nearly a singularity, had adversely affected the capability of the maneuver, thus necessitating the large $\Delta$V. A viable backup maneuver design was found through critical plane targeting. By allowing $\mathbf{B} \cdot \mathbf{R}$ to vary in the maneuver search, the Maneuver Team discovered that modifying $\mathbf{B} \cdot \mathbf{R}$ by $-0.5$ km lowered the $\Delta$V to 0.120 m/s, only twice the size of the prime design. With OTM-268 (over its backup), 0.4 m/s downstream $\Delta$V could be saved, OTM-269 would not become a borderline MEA burn of nearly 0.3 m/s, and the probability of cancelling OTM-271 would increase, easing concerns of a leaking thruster fault scenario.[24] Although performing the maneuver was agreed upon, the final maneuver design would have produced unacceptable RWA speeds. Instead of risking last minute changes to the wheel speeds, the Project decided to revert to the previous designs for both the prime and backup maneuvers based on the preliminary orbit determination (OD) solution, which yielded favorable wheel speeds. This introduced a known 3 km error in the orbit determination at E12, but this was found to be satisfactory.

*Delaying to OTM-269 Backup* Because OTM-269 was scheduled just one day after E12, only one tracking pass was made available to the OD team. Usually, cleanup maneuvers are designed with two full tracks of post-flyby data. Additionally, the backup window, OTM-269 BU, was booked only 14 hours after the prime opportunity, as opposed to the usual 24 hours. However, delaying to the backup opportunity would provide another tracking pass of post-E12 flyby data, thus improving the OD accuracy for the maneuver design. Delaying to OTM-270 to target E13 would cost over 0.4 m/s in downstream $\Delta$V, so either OTM-269 or OTM-269 BU had to be considered. OTM-269 BU was favored over the prime location because of the tight design and implementation schedule. The Project also made this decision because one of the RWA wheel speeds for the prime maneuver design would have dwelled in a low RPM range for an unacceptable period of time.

*Enceladus-13 Time-of-Flight Modification* OTMs 270 and 271 were planned to target the E13 flyby in conjunction with OTM-269. The $\Delta$V cost would have been over 1.2 m/s if OTMs 270 and 271 were cancelled, resulting in a 38 km E13 flyby which was 12 km below the intended 50 km altitude. Initially, OTM-270 was designed to be 3.4 mm/s, under an implementable $\Delta$V of 9 mm/s, so the time of flight of E13 was modified by +0.7 seconds (see Figure 5). The option to wait until OTM-271 to perform a maneuver was dismissed due to the 0.16 m/s added downstream cost, mainly placed in OTM-272, scheduled on Christmas Eve, and OTM-273, scheduled on New Year's Eve. OTM-270 was executed to increase the chance of either skipping OTM-272 or OTM-273, to alleviate any concerns of a leaking thruster fault,[24] and the acceptability of the wheel speeds during the maneuver turns. It marked the fourth time a modification to the encounter arrival time was implemented, and the first time this change was at an earlier targeting opportunity other than the final approach. With only a 1 km correction to the E13 flyby, OTM-271 was too small to be implemented using the modified time of flight introduced with OTM-270's execution. Consequently, the original target time was reinstated to increase OTM-271's $\Delta$V to an executable size. Cancellation provided a slight savings of 56 mm/s, and more importantly, avoided riding out a few regions of low RPM on RWA. With no impact on science, OTM-271 was cancelled.

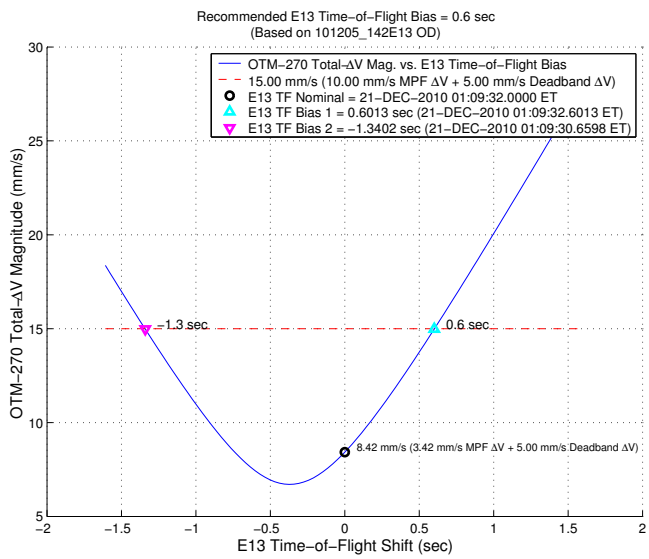



**Figure 5. E13 Time-of-Flight Shift via OTM-270**

*Rhea-3 Flyby Aimpoint Change* OTMs 272, 273, and 274 were scheduled to target the R3 flyby, the last of three consecutive icy satellite encounters. As discussed previously, performing OTM-271 increased the likelihood of cancelling either OTM-272 or OTM-273. Targeting OTM-272 directly to R3 would yield a downstream $\Delta$V cost of nearly 0.4 m/s, but delaying to OTM-273 to target R3 would add virtually no cost. Hence, OTM-272 was cancelled and OTM-273 was performed. Finally, OTM-274, the final approach maneuver to R3, was executed. To save 0.2 m/s which was seen in a $\Delta$V cost vs. R3 aimpoint shift contour plot (see Figure 6), the R3 target was modified by $-5$ km in $\mathbf{B} \cdot \mathbf{R}$ and by $-5$ km in $\mathbf{B} \cdot \mathbf{T}$. This shift produced a better flyby for science at an altitude of 69 km, as opposed to the prescribed 75 km. This science improvement was the primary reason OTM-274 was executed to target the modified aimpoint.

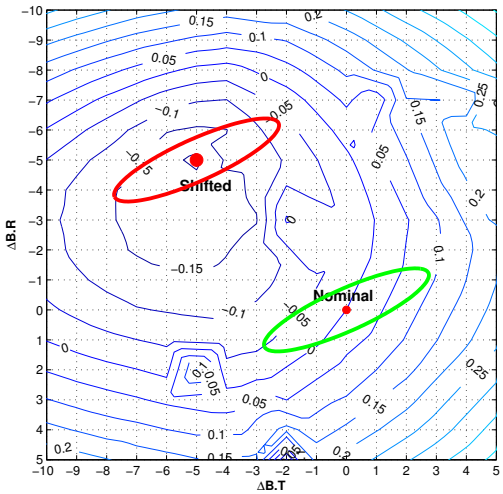



**Figure 6. R3 Cost Contours at OTM-274**

### Alternating Inbound and Outbound Titan Encounters (T74–T77)

The next five encounters involved alternating between inbound and outbound flybys of Titan. This paper covers the first four of these five Titan encounters: T74 through T77. T78, the last of these encounters scheduled on September 12, 2011, will be discussed in a future Cassini maneuver experience paper.

*OTM-275, Last Planned MEA Burn for 8 Months* After nearly two months since the last executed MEA maneuver (OTM-267), OTM-275 was only the second MEA maneuver performed thus far in the Solstice Mission. The next main engine maneuver to be performed is most likely OTM-291 on September 20, 2011 at an approximate 5 m/s. This maneuver is scheduled more than eight months after OTM-275, the longest gap ever between MEA burns in the Saturn tour. OTM-275 was executed to directly target T74, also removing the spacecraft from a Titan impact trajectory.

*Targeting Titan-74* Either OTM-276 or OTM-277 had to be performed to avoid a significant 6.3 m/s downstream cost, to correct 22 km and 2.2 seconds in the T74 B-plane left by OTM-275's execution. This cost was reflected in the growth of OTM-278 to over 4 m/s (reference trajectory $\Delta V$ = 30 mm/s) and OTM-279 to 2 m/s (ref. traj. $\Delta V$ = 8 mm/s). Skipping OTM-276 in favor of OTM-277 to target T74 would add a predicted downstream cost of 0.3 m/s, mainly in the growth of OTM-278 from 0.03 m/s to 0.3 m/s. OTM-276 was designed to be 20.2 mm/s, whereas OTM-276 BU required a TF shift of +0.25 seconds to increase the $\Delta V$ to an implementable size of 16.5 mm/s. The main reason the backup maneuver $\Delta V$ was smaller than the prime was that the central angle at the prime maneuver location was 87.0° and the central angle at the backup was 70.8°. At the prime maneuver location, the gradients of $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and time of flight were highly correlated, whereas they became more separated at the backup maneuver window, thus providing more capability for the maneuver. In the end, the nominal choice of performing the prime over the backup maneuver was made. OTM-276 left the spacecraft within 1 km of the T74 target. OTM-277 was cancelled because there was only a 0.09 m/s cost to cancel and executing OTM-277 required a TF shift of $-0.7$ seconds.

*Titan-75 Aimpoint Change* Foregoing the cleanup maneuver to the T74 flyby would only cost 18 mm/s; hence, OTM-278 was cancelled. Early in OTM-279's design it was noted that a 0.2 m/s savings could be achieved by retargeting to an aimpoint $-12$ km in $\mathbf{B} \cdot \mathbf{R}$ and $-5$ km in $\mathbf{B} \cdot \mathbf{T}$ from the reference target (see Figure 7). OTM-279 was aimed at the modified target as this change would not affect the science planned at T75 and the OTM-279 $\Delta V$ decreased. This marked the second time an aimpoint change was made at an earlier targeting opportunity, OTM-213 being the first.[13]

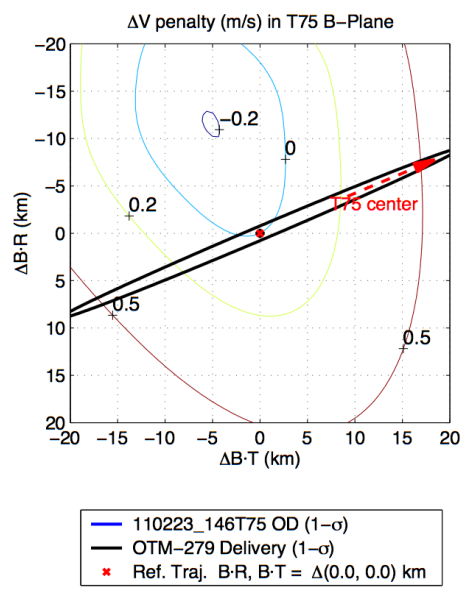



**Figure 7. T75 Cost Contours at OTM-279**

*Saving Hydrazine Via OTM-280* Targeting a high 10053 km Titan flyby with only a ∼4 km miss in the radial direction, OTM-280 was posed for cancellation. However, 75 mm/s in $\Delta$V savings by performing OTM-280, which translates to roughly 75 grams of hydrazine, outweighed any argument to cancel. OTM-280 was performed with no risk to science and the verification of good RWA wheel speeds.

*Titan-76 Time-of-Flight Modification* OTM-281 was one of the rare cases where doing the nominal strategy of optimizing the cleanup maneuver with the apocrone maneuver (OTMs 281 and 282) and downstream maneuvers would cost roughly the same as targeting the cleanup or apocrone maneuver directly to the encounter. As a result, OTM-281 was targeted to T76 to add another statistical maneuver opportunity (OTM-282) for targeting to the T76 aimpoint. Executing OTM-281 left OTM-282 with only 2 km to fix in the T76 flyby, requiring a large $-2$ second modification to the T76 time of flight to increase both OTM-282 and OTM-282 BU to implementable sizes. Because the 2-second change in T76 would not be acceptable for science planning, OTM-282 was cancelled in favor of OTM-283, which only required a $-0.4$ second change in the T76 time of flight to implement. OTM-283 was executed to eliminate a downstream cost of 0.8 m/s, which would force OTMs 284 and 285 to be MEA burns. This maneuver was the fourth smallest burn to date, following OTMs 118, 121, and 139 in 2007.[10,11] The decision to adjust the T76 time of flight was facilitated using a plot of maneuver $\Delta$V vs encounter TF change shown in Figure 8.

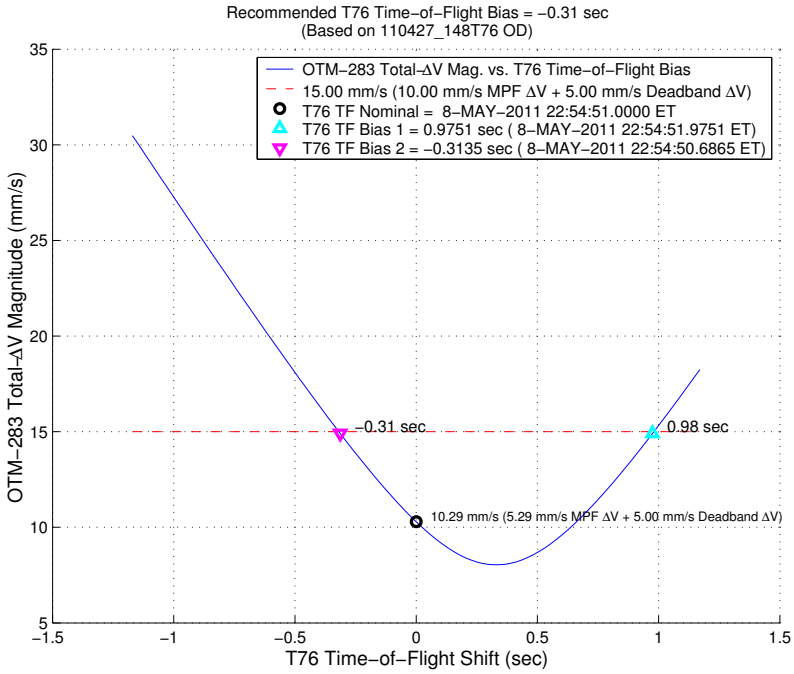



**Figure 8. Titan-76 Time-of-Flight Shift via OTM-283**

*Return to Cleanup Maneuver Optimization Strategy* The T76 flyby left the spacecraft on a Titan impact trajectory, necessitating the execution of either OTM-284 or OTM-285. The cost of cancelling OTM-284 relative to performing both OTMs 284 and 285 was 0.38 m/s, requiring the MEA for OTMs 285 and 287. Targeting T76 with OTM-284 would cost a larger 1.4 m/s $\Delta$V, so the nominal strategy of performing both OTMs 284 and 285 was chosen. OTM-284 marked a return to the cleanup maneuver optimization strategy, and the first time this strategy was utilized in the

Solstice Mission. The last time this strategy was used was near the end of the Equinox Mission with OTM-257, almost a year earlier. OTM-285 became a must-do maneuver because it would cost 15.4 m/s if T77 was left uncorrected. Although OTM-286 presented a slight $\Delta$V savings, the risk of enduring the high downstream cost if it could not be executed nullified this argument. Therefore, OTM-285 was executed, a maneuver with the smallest combination of yaw and roll turns so far in the entire Saturn tour ($-21.8°$ and $-4.7°$, respectively).

*Titan-77 Time-of-Flight Modification; Saving Hydrazine Again* OTM-286 was designed with a $-0.4$ second time of flight shift to T77 to make it implementable, as illustrated in Figure 9. With only a $\sim$0.7 km correction to make, this TF shift represented a change three times greater than this correction (over 2 km). Performing OTM-286 would also save only 90 mm/s. Before the Solstice Mission, this would have been a clear case for cancellation. However, with the precedent set with OTM-280 and the confidence instilled by the better-than-expected OD accuracy, OTM-286 was performed to save the equivalent 90 grams of hydrazine.

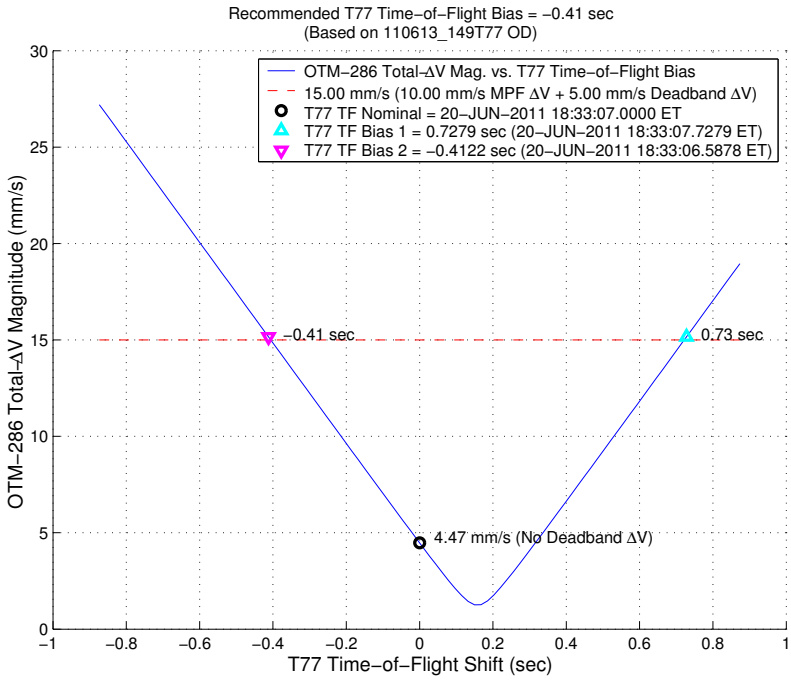



**Figure 9. Titan-77 Time-of-Flight Shift via OTM-286**

## Targeting Titan-78, The Half-Way Mark of First Equatorial Phase

OTM-287 was the last maneuver included in the scope of this paper. Coincidentally, it was the 200th executed OTM of the Cassini tour, not including the 18 executed Trajectory Correction Maneuvers (TCMs) of the interplanetary cruise and the Saturn Orbit Insertion (SOI) maneuver.[5–7] The separation between OTM-287 and the next scheduled maneuver, OTM-288, is two months, the second largest separation between maneuvers since OTMs 024 and 025 in 2005.[8] OTM-287 was executed to target T78 directly. More than likely, at least one additional maneuver will need to be performed to correct the T78 aimpoint error left by OTM-287; this will be discussed in a future Cassini maneuver experience account. The T78 approach was another four-maneuver arc that included OTM-287, 288, 288a, and 289. Similarly with OTM-261a, OTM-288a was booked to mitigate the risk of OTM-289 becoming a required MEA maneuver.

## NAVIGATION PERFORMANCE

Table 4 shows the maneuver performance per encounter. The navigation cost per encounter is the difference between the reference trajectory $\Delta$V, which is deterministic, and the reconstructed $\Delta$V, which is deterministic plus a statistical (random) component. The predicted $\Delta$V statistics per encounter span were garnered from statistical analyses reported in References 4, 16, and later updated from covariance studies during operations.

**Table 4. Maneuver Performance per Encounter**

| Encounter Span | Ref. Traj. Det. $\Delta$V (m/s) | Predicted $\Delta$V Statistics Mean (m/s) | 1-$\sigma$ (m/s) | 95% (m/s) | Design $\Delta$V (m/s) | Recon. $\Delta$V (m/s) | Navigation $\Delta$V Cost* (m/s) |
|---|---|---|---|---|---|---|---|
| T69–T70 | 1.250 | 1.822 | 0.423 | 2.618 | 1.264 | 1.267 | **0.017** |
| T70–T71 | 6.703 | 7.270 | 0.405 | 8.041 | 7.154 | 7.148 | **0.445** |
| T71–E11 | 6.941 | 7.486 | 0.351 | 8.158 | 7.608 | 7.597 | **0.656** |
| E11–T72 | 2.303 | 2.513 | 0.125 | 2.746 | 2.616 | 2.612 | **0.309** |
| T72–T73 | 0.004 | 0.259 | 0.131 | 0.497 | 0.354 | 0.344 | **0.340** |
| T73–E12 | 2.319 | 2.489 | 0.478 | 3.144 | 2.314 | 2.314 | **−0.005** |
| E12–E13 | 0.038 | 0.181 | 0.076 | 0.327 | 0.178 | 0.178 | **0.141** |
| E13–R3 | 0.006 | 0.311 | 0.255 | 0.856 | 0.244 | 0.242 | **0.236** |
| R3–T74 | 2.647 | 3.087 | 0.552 | 4.276 | 2.786 | 2.784 | **0.137** |
| T74–T75 | 0.003 | 0.507 | 0.270 | 1.026 | 0.120 | 0.122 | **0.119** |
| T75–T76 | 0.003 | 0.300 | 0.189 | 0.664 | 0.057 | 0.057 | **0.053** |
| T76–T77 | 0.020 | 1.127 | 0.844 | 2.746 | 0.173 | 0.172 | **0.152** |

* Navigation $\Delta$V cost = reconstructed $\Delta$V − reference trajectory deterministic $\Delta$V. Note, the computed navigation costs are based on the raw numbers to avoid round-off errors.

The average navigation $\Delta$V cost per flyby is summarized in Table 5. The cost between each encounter was not as evenly distributed prior to the Solstice Mission, a fact that can be seen in the large standard deviation of nearly 1 m/s for the Equinox Mission reported in the table. With the majority of the maneuvers performed on RCS during the Solstice Mission (only two MEA have been performed), the average navigation cost so far in the Solstice Mission has been less than half the average cost seen in the prior missions. However, the average navigation cost in the Solstice Mission is likely to increase because of more complex geometries and shorter turn-around times expected to design maneuvers. The current cost only takes into account one-tenth of the entire Solstice Mission. This was a period marked by long orbital transfers which provided more accurate OD data for the maneuver designs.

**Table 5. Average Navigation $\Delta$V Cost per Flyby**

| Mission | Flyby Span | Number of Flybys | Navigation $\Delta$V Cost Average (m/s) | Navigation $\Delta$V Cost Std. Dev. (m/s) |
|---|---|---|---|---|
| Prime (July 2004 – July 2008) | Ta–T44 | 52 | 0.331 | 0.603 |
| Equinox (July 2008 – Sept. 2010) | T45–T72 | 38 | 0.431 | 0.956 |
| Solstice (Sept. 2010 – June 2011) | T73–T77 | 8 | 0.147 | 0.106 |

## CLOSING REMARKS

The Solstice Mission doubles the entire Saturn tour in terms of the science goals, the number of maneuvers, and the number of encounters. Looking forward to a 2017 mission completion date, the Cassini Project modified its rationale for executing or cancelling maneuvers. Beginning with the first few months of the Solstice Mission, downstream propellant preservation by performing maneuvers outweighed concerns of adding maneuver cycles to Cassini. Small $\Delta$V savings, which translated to savings in hydrazine, were achieved mainly by flyby modifications that also preserved the science. This maneuver strategy of altering the encounter conditions, either by a change to the time of flight or changes to the B-plane coordinates ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$), was used sparingly prior to the Solstice Mission. Within just the first nine months of this new extended mission, this strategy has been used six times, matching the number implemented during the Prime and Equinox Missions combined.

The Cassini Navigation Team was able to maintain the prescribed Saturn tour from June 2010 through June 2011 via the successful execution of 27 maneuvers, which targeted 9 Titan flybys and 4 icy satellite encounters (three of Enceladus and one of Rhea). With several Enceladus flybys planned in the second half of 2011, including a double flyby of Dione and Titan in December, the Cassini Navigation Team continues to design maneuvers enabling the science requirements of the Solstice Mission to be achieved.

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