2008-6751

AIAA/AAS Astrodynamics Specialist Conference, 18 - 21 Aug 2008, Honolulu, Hawaii

# Cassini-Huygens Maneuver Experience: Ending the Prime Mission

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**The Cassini-Huygens spacecraft was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year cruise, it entered a Saturnian orbit for a four-year, prime mission. This paper highlights significant maneuver activities performed during the last year of the prime mission. Specifically, results of 42 recent maneuvers are presented. Many maneuvers have been skipped, saving fuel and flight team effort. The system has performed more accurately than the pre-launch expectations and requirements. This is in large part why the Cassini-Huygens spacecraft has been navigated with tremendous success during the prime mission.**

## I. Overview

The Cassini-Huygens spacecraft was launched in 1997 on a mission to observe Saturn and its many moons. After a seven-year cruise, Cassini-Huygens entered orbit around Saturn for a four-year tour. One of the mission's first activities was to release the Huygens probe to Titan, Saturn's largest moon, in 2005. Since then, the Cassini orbiter, see Figure 1, has continued to travel in a series of highly elliptical orbits about Saturn. This series of orbits is referred to as the "satellite tour." The mission is an ongoing study of the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites. The mission has also been examining Titan's atmospheric structure and composition as well as Titan's surface topography.

Earlier papers from the Cassini Navigation Team reported on a prelaunch analysis,[1] maneuvers planned and performed during early interplanetary cruise,[2] inner cruise,[3] and end of cruise with arrival at Saturn.[4] Reports have also covered the first year of Saturn tour,[5] the second year,[6] and the third year,[7] ending at OTM-118 on June 26, 2007. Now, completing its fourth and last year of the prime mission, the Cassini-Huygens mission continues to obtain valuable data on Saturn, Titan, and Saturn's other satellites. Return of this information has been largely due to a healthy spacecraft and successful navigation.

The prime mission ended on July 1, 2008, four years after it began with Saturn Orbit Insertion (SOI) on July 1, 2004. This paper chronicles the most recent year of exploration of the Saturnian system from a maneuver analyst's perspective. The year has included 12 Titan flybys (T33 to T44), an Enceladus flyby (E3), and an Iapetus flyby (I1). Among its highligts are radio science occultations of Titan, an Enceladus plume occultation, radio science occultations of Saturn, and a gradual increase in orbital inclination. At the end of the prime mission, Cassini's orbit was the most inclined it had ever been with respect to Saturn's equator, 74.7°, as plotted in Figure 2.

Figure 3 shows the orbits of this year of the tour. Looking along the line of nodes, the progression of inclination becomes quite clear. An interesting feature is how the longitude of the ascending node (LAAN) of the spacecraft's orbit around Saturn changed sign between T35 and T36. This was done in order to encounter Iapetus on September 10, 2007. Between T33 and T34 the LAAN was about 89° but after T36, the LAAN was kept quite close to 45° as the focus was on increasing orbital inclination.

From June 26, 2008 to June 23, 2008, there were 42 planned Orbit Trim Maneuvers (OTMs). The first Titan encounters (T33-T35) were targeted by OTMs 118 through 124 and ended the rotation of Cassini's

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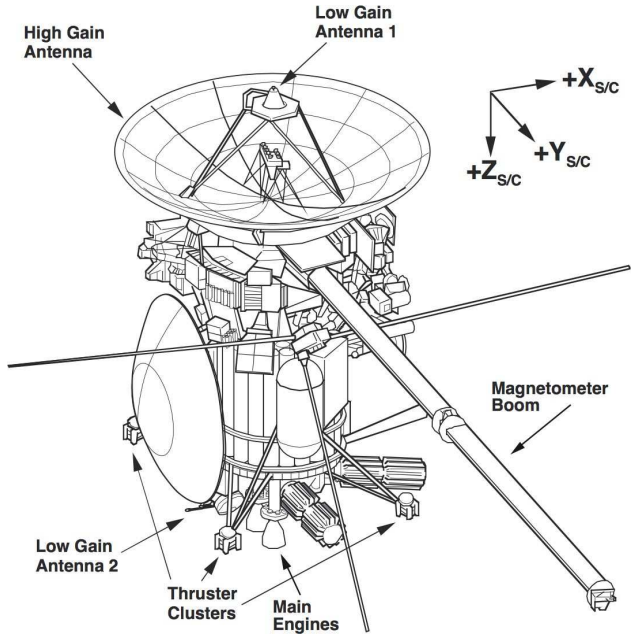


**Figure 1. Cassini-Huygens Spacecraft.** The Huygens probe was released in the first year[5] of the tour

orbit as reported previously.[7] That sequence was followed by an encounter with Iapetus on September 10, 2007, targeted by OTMs 125 though 127. The remaining maneuvers and encounters, though T44 on May 28, 2008, gradually increased inclination. The sequence was briefly interrupted by a flyby of Enceladus on March 12, 2008, between the T41 and T42 encounters. Enceladus was targeted with OTMs 146 though 148. Not all of these maneuvers were executed, some were cancelled after examining the latest orbit estimates, others deleted in advance based on updated predictions.

## II. Maneuver Execution

The Cassini orbiter's Propulsion Module Subsystem (PMS) includes a bipropellant element, the Main Engine Assembly (MEA), for large trajectory corrections and a monopropellant element, the Reaction Control Subsystem (RCS), for small trajectory corrections, attitude control functions, and reaction wheel desaturation. Both are noted on Figure 1. Not shown in the diagram is a clamshell-style cover for the main engine. The cover is typically deployed (closed) between maneuvers and stowed prior to the maneuver's main command sequence.

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

Manevuers are executed in a turn-and-burn style. The burn orientation is achieved by performing a roll turn about the $+Z_{S/C}$ axis followed by a yaw turn about $+Y_{S/C}$ axis. The turns are reversed to return to the nominal attitude. If turns are performed with the RCS thrusters, then the yaw turns will impart $\Delta\mathbf{V}$, requiring that turn angles be computed so that the turn and burn $\Delta\mathbf{V}$ sum properly. Turns performed with the Reaction Wheel Assembly (RWA) don't impart $\Delta\mathbf{V}$. Since cruise, maneuvers using the MEA perform an extra turn of 0.9° to correct for a pointing bias.

The choice of MEA or RCS for a given maneuver is primarily made by the size of the maneuver. If a maneuver $\Delta\mathbf{V}$ magnitude is greater than about 300 mm/s, the choice is MEA, otherwise, RCS. Models of the maneuver execution errors are implemented for statistical analysis and preliminary judgements of maneuver performance. These models have been recently updated[8] based on maneuver performance thus far in the Saturnian tour.

These models are Gates models[9] and account for four independent error sources, fixed- and proportional-

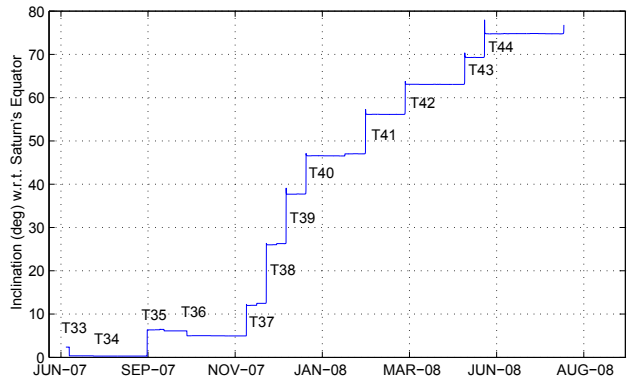


**Figure 2. Inclination** Computed from Saturn-centered, osculating orbit in coordinates of Saturn Equator of Date. Increments are denoted by the encounter that caused them.

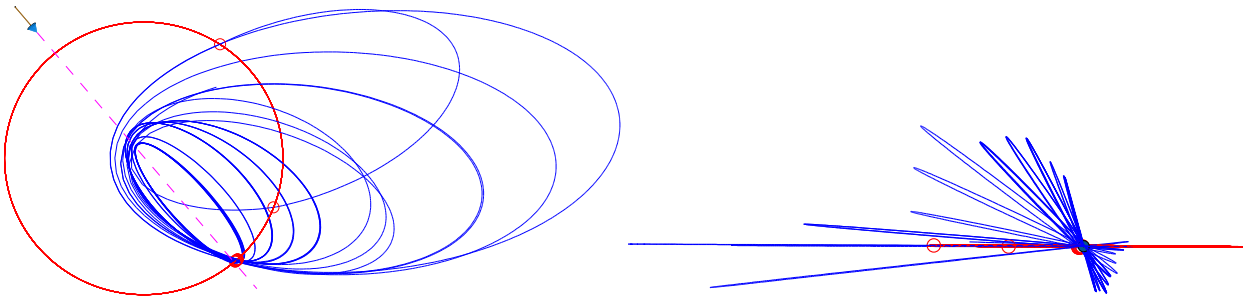

**Figure 3. Trajectory from July 2007 to July 2008** Titan's orbit is shown as a red circle. The Cassini orbiter's trajectory is blue. Titan encounters are marked by small circles. The left-hand view is looking down from Saturn's North pole, the line of nodes for orbits after T36 is indicated by a dashed line. The right-hand view is looking along the line of nodes.

magnitude errors and fixed- and proportional-pointing errors. Four parameters specify the standard deviations for the error sources and each error source is assumed to have a zero mean. All pointing errors are perpendicular to the nominal $\Delta\mathbf{V}$ vector. The direction of pointing errors is assumed to have a uniform distribution across 360°.

The models used over the most recent year are listed in Table 1. The current model, 2007-02, has been in use since OTM-143 in January 2008.[8] It superseded the 2007-01 execution-error model,[10] which had been in use since OTM-125's design in September 2007. The 2006-01 model began use with the design of OTM-53 in March 2006.[11] The only difference between the 2006-01 and 2007-01 models is the proportional-pointing term for RCS maneuvers, which was nulled because RCS maneuvers were executing roll and yaw turns with the RWA system which doesn't produce any $\Delta\mathbf{V}$.

The navigation strategy since launch has been to target the spacecraft to fixed encounter conditions defined in the reference trajectory[a]. These targeted parameters are three B-plane parameters of an upcoming encounter; the spatial components $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ and the temporal component time-of-flight (TF). (For an explanation of the B-plane, see Section X and Ref. 12). $\mathbf{\Delta B}$ is referred to as the B-plane error ($\Delta\mathbf{B}\cdot\mathbf{R}$, $\Delta\mathbf{B}\cdot\mathbf{T}$, and $\Delta$TF) . An exception to this strategy in the last year was OTM-131, which targeted Cartesian $x$, $y$, $z$ coordinates for an Enceladus plume occultation, see Section IX.B.

A strategy involving three propulsive Orbit Trim Maneuvers (OTMs) between each Titan or icy satellite encounter continues to be employed: a flyby-cleanup maneuver and two targeting maneuvers. Past studies have shown that any additional maneuvers between encounters generally do not significantly lower the $\Delta\mathbf{V}$ requirements.[13] Figure 4 illustrates this maneuver strategy for an outbound-to-inbound[b] Titan transfer. The cleanup maneuver, usually three days after an encounter, corrects trajectory errors from the previous

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

[b]An outbound flyby occurs after pericrone. An inbound encounter occurs before pericrone.

**Table 1. Execution-Error Models** given as 1-$\sigma$

| | | RCS | | MEA | |
|---|---|---|---|---|---|
| | | Fixed | Proportional | Fixed | Proportional |
| 2006-01 | Magnitude | 0.9 mm/s | 0.7% | 6.5 mm/s | 0.04% |
| (Mar 06) | Pointing | 3.5 mm/s | 12.0 mrad | 4.5 mm/s | 0.6 mrad |
| 2007-01 | Magnitude | 0.9 mm/s | 0.7% | 6.5 mm/s | 0.04% |
| (Sep 07) | Pointing | 0 mm/s | 12.0 mrad | 4.5 mm/s | 0.6 mrad |
| 2007-02 | Magnitude | 1.0 mm/s | 0.4% | 5.0 mm/s | 0.02% |
| (Jan 08) | Pointing | 0 mm/s | 9.0 mrad | 3.0 mm/s | 0.6 mrad |

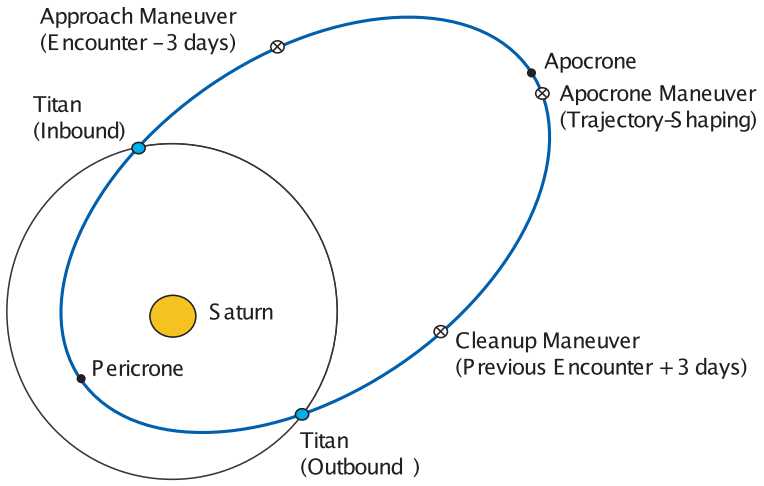


**Figure 4. Maneuver Strategy for Saturn Tour** Shown here is an outbound-to-inbound leg. Inbetween encounters are three maneuvers. The shaping maneuver is also known as the apocrone maneuver.

flyby. The maneuver's location depends on the time required to converge the Orbit Determination (OD) estimate used to design the maneuver, the time required to develop the maneuver, and all other processes through the uplinking of its command sequence. The next maneuver targets the encounter directly and is performed near apocrone (Saturn apoapsis) to shape the trajectory in order to achieve the flyby conditions. The approach maneuver, the last targeting maneuver, is usually executed three days before an encounter. It has the same target as the shaping maneuver did so that it cleans up errors and enables the mission to achieve as accurate flyby conditions as possible. The approach maneuver location avoids interference with science activities during the encounter period and allows enough time to perform a backup maneuver if necessary. All of the mission's OTMs have backup locations.

Cleanup maneuvers are often designed with a chained two-impulse optimization strategy, which minimizes the sum of cleanup and shaping maneuvers across several encounters. This optimization technique helps control errors in the outgoing asymptote of hyperbolic satellite flybys without actively altering downstream flyby aimpoints after each encounter.

The cost function for this optimization problem is as follows:

$$J_i = \underbrace{||\Delta\mathbf{V}_{i_1}|| + ||\Delta\mathbf{V}_{i_2}||}_{segment\ i} + \underbrace{||\Delta\mathbf{V}_{i+1_1}|| + ||\Delta\mathbf{V}_{i+1_2}||}_{segment\ i+1} + \underbrace{||\Delta\mathbf{V}_{i+2_1}|| + ||\Delta\mathbf{V}_{i+2_2}||}_{segment\ i+2} + \quad ... \tag{1}$$

$$= \sum_{m=0}^{n} ||\Delta\mathbf{V}_{i+m_1}|| + ||\Delta\mathbf{V}_{i+m_2}|| \tag{2}$$

subject to the constraints

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+1} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+1} = 0,\ \Delta TF_{i+1} = 0, \tag{3}$$

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+2} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+2} = 0,\ \Delta TF_{i+2} = 0, \quad etc.\ up\ to\ (i+m) \tag{4}$$

It follows that for $n$ downstream encounters (beyond the current encounter), $2(n+1)$ maneuvers are being optimized ($6(n+1)$ parameters) and $3(n+1)$ constraints are imposed. For most cleanup maneuvers during the tour, $n = 4$ so that 10 maneuvers are optimized across five encounters; in the last year, $n = 3$ has been more common, as may be seen in Table 2. Besides providing an optimal distribution of the $\Delta\mathbf{V}$s over multiple legs, this optimization strategy helps control asymptote errors without actively altering downstream flyby aimpoints after each encounter. Another benefit of this strategy is that the designed cleanup maneuver $\Delta\mathbf{V}$s are less sensitive to maneuver time shifts.[14]

**Table 2. Maneuver Optimization Chains** This is a list indicating which chains were used in operations. Note that approach maneuvers are not included in a chain. OTM-126 was deleted and not included in OTM-125's chain. OTM-128 was not optimized, see Section IX.B. OTM-150 was not optimized, see Secion V.

| First Maneuver | Last Maneuver | Number of Maneuvers | Number $n$ of Encounters |
|---|---|---|---|
| OTM-119 | OTM-135 | 12 | 5 |
| OTM-122 | OTM-135 | 10 | 4 |
| OTM-125 | OTM-125 | 1 | 0 |
| OTM-128 | OTM-125 | 1 | 0 |
| OTM-131 | OTM-141 | 8 | 3 |
| OTM-134 | OTM-141 | 6 | 2 |
| OTM-137 | OTM-144 | 6 | 2 |
| OTM-140 | OTM-150 | 8 | 3 |
| OTM-143 | OTM-153 | 8 | 3 |
| OTM-146 | OTM-157 | 8 | 3 |
| OTM-149 | OTM-149 | 1 | 0 |
| OTM-152 | OTM-159 | 6 | 2 |
| OTM-155 | OTM-165 | 8 | 3 |

OTMs 152 and 155 had optimization chains that included OTM-160 and beyond, which were not part of the prime mission, but part of the extended mission, called the Cassini Equinox mission.[15] Maneuvers as far

out as OTM-165 had to be included in optimization chains to connect the prime mission with the Equinox mission. Details of the optimization chain setup of maneuvers in the Equinox mission will be left to a future paper.

## III. Reference Trajectories

The reference trajectories serve as the source for best estimates of geometry and timing for future events, like a closest-approach to Titan; for maneuver-targeting aimpoints; and as the starting point for OD and maneuver statistical analyses.[16] Table 3 lists reference trajectories used during the prime mission and is continued from a previous reporting.[4] Updates to the reference trajectory during the tour were primarily to tweak flyby details or improve some maneuver locations. Such tweaks tended to increase the deterministic $\Delta\mathbf{V}$ cost of the tour; those increments are also listed in the table.

**Table 3. Reference Trajectory History** In the table, $\theta$ refers to the B-plane angle, see Section X.

| Name | Release | Comments | $\Delta\mathbf{V}$ cost |
|---|---|---|---|
| 041001 | Oct 1, 2004 | lowered Tb alt. to 1200 km, increased the Probe-Iapetus distance on Rev. C., T3 alt. raised to 1577 km. | n/a |
| 041210 | Dec 10, 2004 | raised T5 and T7 altitides to 1025 km | -13 m/s |
| 050505 | May 5, 2005 | lowered Tethys 15Te to 1500 km, Hyperion H1 to 500 km and $\theta$ from -152° to 152°, and Enceladus E2 to 175 km and $\theta$ from -160° to 125°. Moved OTM-38 | 9.6 m/s |
| 050720 | July 20, 2005 | raised T7 altitude from 1025 km to 1075 km | -0.2 m/s |
| 060323 | Mar 23, 2006 | raised minimum Titan flyby altitude to 950 km | 7 m/s |
| 070209 | Feb 9, 2007 | raised T32 alt. to 975 km, I1 $\theta$ from 157° to 176° | 15 m/s |
| 070918 | Sep 19, 2007 | raised E3 and E4 alt. to 50 km, moved 23 OTMs | 2.3 m/s |
| 080520 | May 20, 2008 | changed E5 $\theta$ from 70° to 90°. Moved 3 maneuver locations | 1.9 m/s |

## IV. Summary of Navigation Performance

Table 4 lists the targeted encounter conditions and the achieved flyby differences for each encounter from T33 to T44. The $\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and time of closest-approach (TCA) target conditions, expressed in Earth's Mean Orbital Plane and Equinox of J2000.0 (EMO2000) coordinates, were defined in the reference trajectories and used in the final maneuver designs. The aimpoints are depicted in Figure 5 with a B-plane mapping relative to Titan's Equator to illustrate the geometry of these flybys. In Table 4, the flyby differences from the reference trajectory represent flyby errors for nominally targeted encounters; for biased targets they represent the shifts due to the biasing in addition to the flyby errors. The hyperbolic excess velocity at the incoming asymptote of an encounter ($\mathbf{V}_\infty$) is also provided in the table for each flyby.

The design characteristics for all maneuvers performed from July 2007 to June 2008 are summarized in Table 5. These attributes include the maneuver epoch; the engine type (MEA or RCS); the true anomaly; the central angle; the design total $\Delta\mathbf{V}$ magnitude, right ascension (RA), and declination (DEC); and the roll and yaw turn angles for the spacecraft burn attitude. The true anomaly listed is for an osculating conic centered at Saturn. The central angle for a maneuver is defined as the angle $\angle$(maneuver location)-Saturn-(target location); measured from the maneuver location to the target location and it counts multiple revolutions; the target is most often a Titan encounter. Observe that of the 42 maneuvers planned, a total of 30 maneuvers were performed. Twenty maneuvers were implemented with the MEA while 10 maneuvers used the RCS. Performing the majority of these maneuvers with the MEA was advantageous because it allowed RCS hydrazine savings.

Tables 6-7 give the history of OTM-118 to OTM-159 in terms of $\Delta\mathbf{V}$, separated by encounters (encounter times in ephemeris time, true anomaly, flyby altitudes, and number of days to next encounter). In the tables, the location of each maneuver in the orbit is given with the corresponding epoch time. The true anomaly

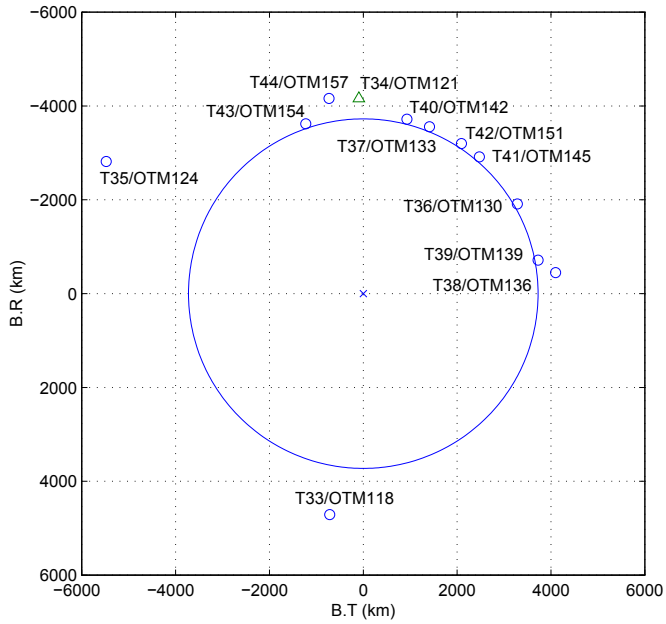


**Figure 5. B-plane Aimpoints for Titan Flybys** Plotted in Titan Equator of Date. Labels indicate the encounter and approach maneuver. All were outbound encounters except for T34, which was inbound.

provides a picture of 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). Each $\Delta\mathbf{V}$ value listed is the total $\Delta\mathbf{V}$ (sum of the burn, turns, including the pointing-bias-fix turn for MEA, and $\Delta\mathbf{V}$s due to dead-band tightening/limit-cycling for RCS burns). The predicted $\Delta\mathbf{V}$ mean, 1-$\sigma$, and 95%[c] values were computed via LAMBIC [d] using the latest reference trajectories. These statistical $\Delta\mathbf{V}$ predictions account for both maneuver execution errors and orbit determination (OD) statistical variations. The design $\Delta\mathbf{V}$s, computed using DPTRAJ,[17] were commanded to the spacecraft. The reconstructed $\Delta\mathbf{V}$s were determined by the OD trajectory smoothing after the maneuvers were performed. Since the reconstructed and predicted $\Delta\mathbf{V}$s include maneuver execution errors, the reconstructed $\Delta\mathbf{V}$s, as opposed to the design $\Delta\mathbf{V}$s, were compared to the predicted $\Delta\mathbf{V}$s to determine the predicted $\Delta\mathbf{V}$ errors. Details on the cancellation and deletion process are described in subsequent sections.

To compare the maneuver performance per encounter, Table 8 lists the reference trajectory deterministic $\Delta\mathbf{V}$s (computed by CATO[e]) and design and reconstructed $\Delta\mathbf{V}$s. The reference trajectory deterministic $\Delta\mathbf{V}$ only includes the cleanup and trajectory-shaping maneuvers, whereas the reconstructed $\Delta\mathbf{V}$ incorporates the deterministic and statistical parts of all maneuvers. Interestingly, the navigation $\Delta\mathbf{V}$ costs for most of the encounter spans were less than 1 m/s, which shows that the tour usually incurs less than 1 m/s per encounter. Any negative value $\Delta\mathbf{V}$ denotes propellant savings due to maneuver cancellations and/or biasing.

When a maneuver design produces a very small $\Delta\mathbf{V}$, analysis for maneuver biasing or cancellation is conducted. A maneuver bias is considered for implementation if the $\Delta\mathbf{V}$ is smaller than 9 mm/s and there is a need to meet flyby accuracy requirements for science observations. A maneuver design bias entails a change in the target time to increase the maneuver magnitude. Cancellation reduces spacecraft use and ground-system stress at moderate propellant cost. Cancellation takes place only after considering several factors. Consideration is given to maneuver magnitude, whether the resulting trajectory deviations are acceptable, deviations in the next target's B-plane asymptote, pointing requirements for science observations, effects on downstream maneuvers and $\Delta\mathbf{V}$ penalty. Cancellation that occurs far in advance of the maneuver is referred to as Deletion.

[c]95% $\Delta\mathbf{V}$ means that the maneuver $\Delta\mathbf{V}$ size will be less than or equal to this value with a 95% probability.

[d]Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC) is a program that simulates the execution of a sequence of maneuvers by computing the statistics of $\Delta\mathbf{V}$ magnitude and delivery accuracy using a Monte Carlo method, see Ref. 16.

[e]CATO (Computer Algorithm for Trajectory Optimization) is a medium-precision trajectory optimization program.

**Table 4. Targeted Encounter History (Titan-33 to Titan-44)**

| Encounter | | $\mathbf{V}_\infty$ | Reference Trajectory Target Conditions (Earth Mean Orbital Plane and Equinox of J2000.0) | | | | Flyby Differences from Reference Trajectory | | |
|---|---|---|---|---|---|---|---|---|---|
| I = Inbound | | $(\frac{km}{s})$ | B·R | B·T | Time of Closest | Altitude | B·R | B·T | TCA |
| O = Outbound | | | (km) | (km) | Approach (ET/SCET)* | (km)† | (km) | (km) | (s) |
| T33 | O | 5.84 | -2655.50 | 3954.85 | 29-JUN-2007 17:00:51 | 1932 | 0.06 | 0.28 | -4e-3 |
| T34§ | I | 5.85 | 530.95 | -4127.55 | 19-JUL-2007 01:12:25 | 1332 | -0.28 | 0.21 | 0.18 |
| T35‡ | O | 5.82 | -4075.95 | -4619.26 | 31-AUG-2007 06:33:39 | 3326 | -1.69 | 4.51 | 1.80 |
| I1‡ | O | 2.34 | 799.05 | -2245.86 | 10-SEP-2007 14:16:45 | 1644 | -0.14 | -7.38 | 8.43 |
| T36 | O | 5.88 | 3744.17 | -652.74 | 02-OCT-2007 04:43:48 | 975 | -2.14 | -0.82 | 0.06 |
| T37 | O | 5.88 | 2533.97 | -2866.69 | 19-NOV-2007 00:48:30 | 1000 | -0.39 | 0.45 | 0.01 |
| T38 | O | 5.90 | 4040.65 | 827.48 | 05-DEC-2007 00:07:55 | 1300 | -1.90 | 1.00 | -0.09 |
| T39 | O | 5.91 | 3756.11 | 531.16 | 20-DEC-2007 22:59:00 | 970 | -0.45 | -0.32 | -0.05 |
| T40‡ | O | 5.90 | 2162.62 | -3166.55 | 05-JAN-2008 21:31:25 | 1010 | -2.97 | -6.94 | -0.37 |
| T41 | O | 5.92 | 3207.07 | -2080.45 | 22-FEB-2008 17:33:12 | 1000 | -2.70 | -3.80 | -0.08 |
| E3‡ | I | 14.41 | 88.66 | 290.09 | 12-MAR-2008 19:07:17 | 56 | 0.64 | -2.37 | 0.02 |
| T42‡ | O | 5.93 | 2806.42 | -2594.81 | 25-MAR-2008 14:28:53 | 1000 | | | |
| T43‡ | O | 5.92 | -631.49 | -3770.16 | 12-MAY-2008 10:03:03 | 1000 | | | |
| T44 | O | 5.92 | -615.54 | -4178.73 | 28-MAY-2008 08:25:37 | 1400 | | | |

* Ephemeris Time (ET) / Spacecraft Event Time (SCET).

‡ Flyby differences from reference trajectory target conditions may appear large due to cancelled maneuver(s).

§ Reference trajectory target conditions not implemented (e.g., biased approach maneuver).

## V. Cancelled Maneuvers

Tables 6 and 7 note the OTMs that have been cancelled in this fourth year of the tour. Most OTMs were cancelled solely on the basis of downstream $\Delta\mathbf{V}$ cost. Other cancellation decisions were more complicated. None of the shaping maneuvers were cancelled this year. OTM-123 is listed as cancelled, but that was not a cancellation by intent. OTM-123 was cancelled because it's uplink pass was lost. OTM-123-BU (OTM-123 backup) was performed, instead, see Section VIII. Table 9 summarizes the cancelled maneuvers and includes the magnitude of the maneuver when cancellation was decided and the $\Delta\mathbf{V}$ cost of cancellation for each maneuver. The results show that most cancelled maneuvers were approach maneuvers and about half the maneuvers cancelled incurred a small cost while the other half brought small savings.

For OTM-122, the OD uncertainty was an important factor in the decision to cancel. There was not a clear benefit between targeting to T35 using the optimization strategy vs. canceling OTM-122 with OTM-123 performing the entire correction. While the optimization strategy suggested a deterministic savings of 0.46 m/s, the statistical costs were on par with this value - thereby reducing confidence in the ability to actually realize this savings. If the savings were unlikely to be realized, then the project would benefit more by reducing stress on the ground system via cancellation.

For OTMs 140 and 158, the navigation performance for the prior flybys, T39 and T44, respectively, was quite good. In neither case was the maneuver required to maintain the spacecraft on the reference trajectory. For OTM-140, a small, 1 mm/s cost was predicted. For OTM-158, a small savings of 64 mm/s was predicted. Furthermore, OTM-140 would've been too small execute, being 0.4 mm/s (also too small for Table 9).

For OTMs 124 and 127, science return was an important factor. OTM-124 preceded a non-targeted flyby of Rhea before it's flyby of Titan. OTM-127 was to target Iapetus and ensure a desired geometry for an occultation. In both cases, navigation performance prior to the maneuver was sufficient and no clear improvement to the science was to be had by executing the maneuver.

OTM-142 also benefited from prior performance. In this case it was OTM-141, an shaping maneuver, that had such small execution errors. Furthermore, the prior flyby error (T40) was such that downstream $\Delta\mathbf{V}$ would be a little smaller than previously predicted and the spacecraft would be even a little closer to the reference trajectory without OTM-142.

OTM-148 was cancelled, not by intent, but due to OD concerns, see Section VIII. OTM-148-BU would've have been executed in its place, but it was cancelled. It would not have appreciably improved the odds of coming closer to the aimpoint, the downstream $\Delta\mathbf{V}$ cost was lower without the maneuver. Science planning

**Table 5. Maneuver Design Characteristics** a B indicates a backup maneuver, as in OTM-123B

| Maneuver | Maneuver Epoch (UTC/SCET)* | Burn Type | True Anom. (deg) | Central Angle (deg) | Total $\Delta\mathbf{V}$ (Burn + Turns)† Mag. (m/s) | RA (deg) | DEC (deg) | Roll Turn (deg) | Yaw Turn (deg) |
|---|---|---|---|---|---|---|---|---|---|
| OTM-118 | 26-Jun-2007 23:08 | RCS | -141.41 | 292.32 | 0.013 | 150.40 | -4.27 | 35.72 | -159.48 |
| OTM-119 | 03-Jul-2007 22:37 | RCS | 165.60 | 53.37 | 0.023 | 121.00 | -30.24 | 146.47 | -128.92 |
| OTM-120 | 08-Jul-2007 22:22 | DELETED | | | | | | | |
| OTM-121 | 15-Jul-2007 22:06 | RCS | -161.93 | 20.91 | 0.013 | 61.91 | -2.43 | 87.36 | -94.59 |
| OTM-122 | 21-Jul-2007 21:36 | RCS | 109.15 | 376.32 | CANCELLED | | | | |
| OTM-123 | 05-Aug-2007 20:35 | MEA | 174.68 | 310.77 | DELAYED | | | | |
| OTM-123B | 06-Aug-2007 20:35 | MEA | 176.09 | 309.36 | 0.431 | 197.99 | 7.72 | -90.48 | -130.09 |
| OTM-124 | 27-Aug-2007 19:20 | RCS | -125.49 | 250.95 | CANCELLED | | | | |
| OTM-125 | 02-Sep-2007 11:35 | MEA | 149.43 | 23.29 | 0.487 | 159.29 | 38.64 | 21.70 | -151.93 |
| OTM-126 | 05-Sep-2007 18:50 | DELETED | | | | | | | |
| OTM-127 | 08-Sep-2007 18:50 | RCS | 169.16 | 3.57 | CANCELLED | | | | |
| OTM-128 | 13-Sep-2007 18:20 | MEA | 178.78 | 312.03 | 13.482 | 311.53 | 65.12 | 176.63 | -76.74 |
| OTM-129 | 17-Sep-2007 18:21 | RCS | -174.29 | 305.10 | 0.103 | 64.67 | -46.13 | 131.51 | -81.67 |
| OTM-130 | 28-Sep-2007 17:36 | RCS | -131.09 | 261.91 | 0.024 | 289.38 | 64.44 | -29.25 | -83.61 |
| OTM-131 | 05-Oct-2007 17:22 | MEA | 162.16 | 696.50 | 1.331 | 301.76 | 35.59 | 117.57 | -54.72 |
| OTM-132 | 01-Nov-2007 15:40 | MEA | 171.38 | 327.25 | 0.982 | 276.04 | -49.03 | -139.13 | -61.96 |
| OTM-133 | 15-Nov-2007 14:56 | RCS | -138.43 | 277.08 | 0.067 | 245.23 | -4.43 | -73.25 | -93.53 |
| OTM-134 | 22-Nov-2007 06:57 | MEA | 169.84 | 340.63 | 1.172 | 352.70 | 34.35 | 16.88 | -43.50 |
| OTM-135 | 27-Nov-2007 06:43 | MEA | -173.75 | 324.23 | 15.764 | 281.77 | 62.57 | -85.34 | -82.83 |
| OTM-136 | 02-Dec-2007 13:44 | RCS | -132.10 | 282.60 | 0.018 | 188.71 | 16.22 | -79.83 | -151.75 |
| OTM-137 | 08-Dec-2007 06:00 | MEA | 168.95 | 338.52 | 0.680 | 193.22 | 11.87 | -42.78 | -146.22 |
| OTM-138 | 13-Dec-2007 07:10 | MEA | -172.62 | 320.09 | 9.643 | 254.20 | 74.23 | -105.79 | -96.27 |
| OTM-139 | 18-Dec-2007 05:16 | RCS | -133.80 | 281.32 | 0.014 | 130.90 | 55.28 | -136.62 | -128.95 |
| OTM-140 | 24-Dec-2007 05:02 | RCS | 167.46 | 334.97 | CANCELLED | | | | |
| OTM-141 | 29-Dec-2007 12:02 | MEA | -169.48 | 311.91 | 2.052 | 193.05 | 68.10 | -102.30 | -116.00 |
| OTM-142 | 03-Jan-2008 04:18 | RCS | -119.08 | 261.57 | CANCELLED | | | | |
| OTM-143 | 16-Jan-2008 04:15 | MEA | 79.46 | 1151.31 | 2.881 | 129.56 | -1.65 | -138.83 | -145.46 |
| OTM-144 | 06-Feb-2008 02:06 | MEA | -159.10 | 669.58 | 37.397 | 214.99 | 35.45 | -53.29 | -121.54 |
| OTM-145 | 19-Feb-2008 08:36 | MEA | -143.34 | 293.95 | 0.299 | 64.97 | 36.86 | 80.44 | -92.72 |
| OTM-146 | 01-Mar-2008 22:56 | MEA | -73.68 | 405.80 | 7.028 | 225.64 | -44.76 | -78.61 | -94.08 |
| OTM-147 | 07-Mar-2008 07:21 | MEA | 178.33 | 153.87 | 1.121 | 338.72 | 74.48 | 90.27 | -83.99 |
| OTM-148 | 10-Mar-2008 07:06 | RCS | -157.35 | 129.54 | DELAYED | | | | |
| OTM-148B | 11-Mar-2008 07:06 | RCS | -143.30 | 115.47 | CANCELLED | | | | |
| OTM-149 | 13-Mar-2008 23:21 | MEA | 132.19 | 379.34 | 2.760 | 166.45 | 23.89 | 157.78 | -163.18 |
| OTM-150 | 18-Mar-2008 06:35 | RCS | -179.40 | 330.95 | 0.054 | 192.58 | -38.75 | 90.38 | -118.73 |
| OTM-151 | 22-Mar-2008 22:50 | RCS | -107.67 | 259.30 | CANCELLED | | | | |
| OTM-152 | 11-Apr-2008 01:04 | MEA | -82.34 | 1316.23 | 3.329 | 345.96 | 21.69 | 58.92 | -33.15 |
| OTM-153 | 26-Apr-2008 03:47 | MEA | -176.31 | 690.04 | 0.512 | 330.97 | -34.46 | -80.25 | -19.09 |
| OTM-154 | 09-May-2008 03:00 | RCS | -123.04 | 276.84 | CANCELLED | | | | |
| OTM-155 | 17-May-2008 01:20 | MEA | -135.24 | 658.11 | 1.176 | 339.37 | 26.32 | 29.93 | -36.49 |
| OTM-156 | 22-May-2008 02:13 | RCS | -178.89 | 341.86 | 0.196 | 164.66 | -12.02 | 16.73 | -153.52 |
| OTM-157 | 25-May-2008 01:58 | RCS | -133.05 | 296.05 | CANCELLED | | | | |
| OTM-158 | 01-Jun-2008 00:27 | RCS | -141.35 | 3189.83 | CANCELLED | | | | |
| OTM-159 | 23-Jun-2008 06:24 | MEA | -45.39 | 2014.64 | 12.185 | 32.83 | 64.36 | 88.14 | -84.74 |

* Coordinated universal time (UTC) / spacecraft event time (SCET).

† $\Delta\mathbf{V}$ expressed in Earth Mean Equator and Equinox of J2000.0 coordinates (EME2000).
Mag. = $\Delta\mathbf{V}$ magnitude, RA = right ascension, DEC = declination.

‡ Maneuver performed on backup time.

**Table 6. Maneuver History**

| Maneuver | Orbit Location | Maneuver Time (UTC/SCET)* | True Anom. (deg) | Predicted $\Delta\mathbf{V}$ Statistics Mean (m/s) | 1-$\sigma$ (m/s) | 95% (m/s) | Design $\Delta\mathbf{V}$ (m/s) | Recon. $\Delta\mathbf{V}$ (m/s) | Pred. Error ($\sigma$)† | Burn Type |
|---|---|---|---|---|---|---|---|---|---|---|
| OTM-118 | T33-3d | 26-Jun-2007 23:08 | -141.41 | 0.046 | 0.030 | 0.105 | 0.013 | 0.013 | 1.112 | RCS |
| *Titan-33* | *29-Jun-2007 17:00:51 ET* | | *146.35* | *Alt. = 1932 km* | | *Outbound* | *19.3 days to T34* | | | |
| OTM-119 | T33+3d | 03-Jul-2007 22:37 | 165.60 | 0.939 | 0.646 | 2.177 | 0.023 | 0.024 | 1.416 | RCS |
| OTM-120 | T33∼apo | 08-Jul-2007 22:22 | | 0.023 | 0.019 | 0.061 | ..... *DELETED* ..... | | | |
| OTM-121 | T34-3d | 15-Jul-2007 22:06 | -161.93 | 0.025 | 0.012 | 0.047 | 0.013 | 0.014 | 0.982 | RCS |
| *Titan-34* | *19-Jul-2007 01:12:25.39 ET* | | *-134.65* | *Alt. = 1332 km* | | *Inbound* | *43.2 days to T35* | | | |
| OTM-122 | T34+3d | 21-Jul-2007 21:36 | 109.15 | 1.037 | 0.744 | 2.513 | ..... *CANCELLED* ..... | | | |
| OTM-123 | T34∼apo | 05-Aug-2007 20:35 | 174.68 | ..... *DELAYED* ..... | | | | | | |
| OTM-123B | T34∼apo | 06-Aug-2007 20:35 | 176.09 | 0.379 | 0.238 | 0.836 | 0.431 | 0.427 | 0.201 | MEA |
| OTM-124 | T35-3d | 27-Aug-2007 19:20 | -125.49 | 0.090 | 0.066 | 0.218 | ..... *CANCELLED* ..... | | | |
| *Titan-35* | *31-Aug-2007 06:33:39 ET* | | *128.01* | *Alt. = 3326 km* | | *Outbound* | *10.3 days to I1* | | | |
| OTM-125 | T35+2d | 02-Sep-2007 11:35 | 149.43 | 0.480 | 0.301 | 1.033 | 0.487 | | *0.023* | MEA |
| OTM-126 | T35+5d | 05-Sep-2007 18:50 | | 0.434 | 0.352 | 1.108 | ..... *DELETED* ..... | | | |
| OTM-127 | I1-2d | 08-Sep-2007 18:50 | 169.16 | 0.075 | 0.040 | 0.152 | ..... *CANCELLED* ..... | | | |
| *Iapetus-1* | *10-Sep-2007 14:16:45 ET* | | *173.02* | *Alt. = 1644 km* | | *Outbound* | *21.6 days to T36* | | | |
| OTM-128 | I1+3d | 13-Sep-2007 18:20 | 178.78 | 10.132 | 1.169 | 11.767 | 13.482 | | *2.865* | MEA |
| OTM-129 | I1+6d | 17-Sep-2007 18:21 | -174.29 | 2.995 | 0.977 | 4.823 | 0.103 | 0.103 | 2.959 | RCS |
| OTM-130 | T36-3d | 28-Sep-2007 17:36 | -131.09 | 0.053 | 0.033 | 0.118 | 0.024 | 0.024 | 0.849 | RCS |
| *Titan-36* | *02-Oct-2007 04:43:48 ET* | | *135.87* | *Alt. = 975 km* | | *Outbound* | *47.8 days to T37* | | | |
| OTM-131 | T36+3d | 05-Oct-2007 17:22 | 162.16 | 1.626 | 0.264 | 2.134 | 1.331 | 1.327 | 1.135 | MEA |
| OTM-132 | T36∼apo | 01-Nov-2007 15:40 | 171.38 | 1.062 | 0.157 | 1.328 | 0.982 | 0.977 | 0.543 | MEA |
| OTM-133 | T37-3d | 15-Nov-2007 14:56 | -138.43 | 0.064 | 0.046 | 0.155 | 0.067 | 0.068 | 0.067 | RCS |
| *Titan-37* | *19-Nov-2007 00:48:30 ET* | | *145.66* | *Alt. = 1000 km* | | *Outbound* | *16.0 days to T38* | | | |
| OTM-134 | T37+3d | 22-Nov-2007 06:57 | 169.84 | 1.172 | 0.745 | 2.501 | 1.172 | 1.173 | 0.000 | MEA |
| OTM-135 | T37∼apo | 27-Nov-2007 06:43 | -173.75 | 15.842 | 0.139 | 16.057 | 15.764 | 15.762 | 0.572 | MEA |
| OTM-136 | T38-3d | 02-Dec-2007 13:44 | -132.10 | 0.083 | 0.054 | 0.189 | 0.018 | 0.014 | 1.280 | RCS |
| *Titan-38* | *05-Dec-2007 00:07:55 ET* | | *149.82* | *Alt. = 1300 km* | | *Outbound* | *15.9 days to T39* | | | |
| OTM-137 | T38+3d | 08-Dec-2007 06:00 | 168.95 | 0.897 | 0.720 | 2.283 | 0.680 | 0.681 | 0.300 | MEA |
| OTM-138 | T38∼apo | 13-Dec-2007 07:10 | -172.62 | 9.577 | 0.157 | 9.767 | 9.643 | 9.636 | 0.374 | MEA |
| OTM-139 | T39-3d | 18-Dec-2007 05:16 | -133.80 | 0.049 | 0.032 | 0.110 | 0.014 | 0.014 | 1.132 | RCS |
| *Titan-39* | *20-Dec-2007 22:59:00 ET* | | *145.07* | *Alt. = 970 km* | | *Outbound* | *15.9 days to T40* | | | |
| OTM-140 | T39+3d | 24-Dec-2007 05:02 | 167.46 | 0.867 | 0.807 | 2.440 | ..... *CANCELLED* ..... | | | |
| OTM-141 | T39∼apo | 29-Dec-2007 12:02 | -169.48 | 1.920 | 0.238 | 2.225 | 2.052 | 2.046 | 0.533 | MEA |
| OTM-142 | T40-3d | 03-Jan-2008 04:18 | -119.08 | 0.028 | 0.016 | 0.058 | ..... *CANCELLED* ..... | | | |
| *Titan-40* | *05-Jan-2008 21:31:25 ET* | | *145.93* | *Alt. = 1010 km* | | *Outbound* | *47.8 days to T41* | | | |

* Coordinated Universal Time (UTC) / Spacecraft Event Time (SCET).

† Predicted $\Delta\mathbf{V}$ Error = |Reconstructed $\Delta\mathbf{V}$ - Predicted $\Delta\mathbf{V}$ Mean| / Predicted $\Delta\mathbf{V}$ 1-$\sigma$.

‡ Maneuver performed on backup time.

**Table 7. Maneuver History**

| Maneuver | Orbit Location | Maneuver Time (UTC/SCET)* | True Anom. (deg) | Predicted $\Delta\mathbf{V}$ Statistics Mean (m/s) | 1-$\sigma$ (m/s) | 95% (m/s) | Design $\Delta\mathbf{V}$ (m/s) | Recon. $\Delta\mathbf{V}$ (m/s) | Pred. Error ($\sigma$)† | Burn Type |
|---|---|---|---|---|---|---|---|---|---|---|
| OTM-143 | T40∼per | 16-Jan-2008 04:15 | 79.46 | 2.888 | 0.200 | 3.240 | 2.881 | 2.879 | 0.049 | MEA |
| OTM-144 | T40∼apo | 06-Feb-2008 02:06 | -159.10 | 37.615 | 0.343 | 38.188 | 37.397 | 37.406 | 0.608 | MEA |
| OTM-145 | T41-3d | 19-Feb-2008 08:36 | -143.34 | 0.239 | 0.178 | 0.578 | 0.299 | 0.291 | 0.294 | MEA |
| *Titan-41* | *22-Feb-2008 17:33:12 ET* | | *149.69* | *Alt. = 1000 km* | | *Outbound* | | *19.1 days to E3* | | |
| OTM-146 | T41∼per | 01-Mar-2008 22:56 | -73.68 | 6.602 | 0.303 | 7.241 | 7.028 | 7.021 | 1.379 | MEA |
| OTM-147 | T41∼apo | 07-Mar-2008 07:21 | 178.33 | 0.630 | 0.521 | 1.611 | 1.121 | 1.120 | 0.941 | MEA |
| OTM-148 | E3-3d | 10-Mar-2008 07:06 | -157.35 | ..... *DELAYED* ..... | | | | | | |
| OTM-148B | E3-2d | 11-Mar-2008 07:06 | -143.30 | 0.048 | 0.029 | 0.104 | ..... *CANCELLED* ..... | | | |
| *Enceladus-3* | *12-Mar-2008 19:07:17 ET* | | *-27.80* | *Alt. = 56 km* | | *Inbound* | | *12.8 days to T42* | | |
| OTM-149 | E3+1d | 13-Mar-2008 23:21 | 132.19 | 2.840 | 0.112 | 3.030 | 2.760 | 2.753 | 0.781 | MEA |
| OTM-150 | E3∼apo | 18-Mar-2008 06:35 | -179.40 | 0.104 | 0.061 | 0.220 | 0.054 | 0.055 | 0.792 | RCS |
| OTM-151 | T42-3d | 22-Mar-2008 22:50 | -107.67 | 0.011 | 0.006 | 0.023 | ..... *CANCELLED* ..... | | | |
| *Titan-42* | *25-Mar-2008 14:28:53 ET* | | *150.24* | *Alt. = 1000 km* | | *Outbound* | | *47.8 days to T43* | | |
| OTM-152 | T42∼per | 11-Apr-2008 01:04 | -82.34 | 3.387 | 0.395 | 3.851 | 3.329 | | *0.147* | MEA |
| OTM-153 | T42∼apo | 26-Apr-2008 03:47 | -176.31 | 1.303 | 1.621 | 4.653 | 0.512 | | *0.488* | MEA |
| OTM-154 | T43-3d | 09-May-2008 03:00 | -123.04 | 0.032 | 0.024 | 0.079 | ..... *CANCELLED* ..... | | | |
| *Titan-43* | *12-May-2008 10:03:03 ET* | | *156.36* | *Alt. = 1000 km* | | *Outbound* | | *15.9 days to T44* | | |
| OTM-155 | T43+5d | 17-May-2008 01:20 | -135.24 | 1.019 | 0.297 | 1.398 | 1.176 | 1.173 | 0.518 | MEA |
| OTM-156 | T43∼apo | 22-May-2008 02:13 | -178.89 | 0.875 | 0.821 | 2.679 | 0.196 | | *0.827* | RCS |
| OTM-157 | T44-3d | 25-May-2008 01:58 | -133.05 | 0.014 | 0.008 | 0.029 | ..... *CANCELLED* ..... | | | |
| *Titan-44* | *28-May-2008 08:25:37 ET* | | *164.53* | *Alt. = 1400 km* | | *Outbound* | | *0.0 days to T44* | | |
| OTM-158 | T44+4d | 01-Jun-2008 00:27 | -141.35 | 0.366 | 0.422 | 1.211 | ..... *CANCELLED* ..... | | | |
| OTM-159 | T44∼per | 23-Jun-2008 06:24 | -45.39 | 12.120 | 0.233 | 12.553 | 12.185 | | *0.281* | MEA |

* Coordinated Universal Time (UTC) / Spacecraft Event Time (SCET).

† Predicted $\Delta\mathbf{V}$ Error = |Reconstructed $\Delta\mathbf{V}$ - Predicted $\Delta\mathbf{V}$ Mean| / Predicted $\Delta\mathbf{V}$ 1-$\sigma$.

‡ Maneuver performed on backup time.

**Table 8. Maneuver Performance per Encounter**

| Encounter Span | Ref. Traj. Det. $\Delta\mathbf{V}$ (m/s) | Predicted $\Delta\mathbf{V}$ Statistics Mean (m/s) | 1-$\sigma$ (m/s) | 95% (m/s) | Design $\Delta\mathbf{V}$ (m/s) | Recon. $\Delta\mathbf{V}$ (m/s) | Navigation $\Delta\mathbf{V}$ Cost* (m/s) |
|---|---|---|---|---|---|---|---|
| T32-T33 | 8.215 | 9.793 | 1.200 | 12.142 | 8.736 | 8.730 | 0.514 |
| T33-T34 | 0.011 | 0.987 | 0.648 | 2.219 | 0.036 | 0.038 | 0.027 |
| T34-T35 | 0.018 | 1.506 | 0.954 | 3.366 | 0.431 | 0.427 | 0.409 |
| T35-I1 | 0.003 | 0.989 | 0.441 | 1.831 | 0.487 | 0.488 | 0.485 |
| I1-T36 | 13.430 | 13.179 | 0.255 | 13.462 | 13.609 | 13.597 | 0.167 |
| T36-T37 | 2.468 | 2.753 | 0.337 | 3.367 | 2.380 | 2.371 | -0.097 |
| T37-T38 | 16.976 | 17.098 | 0.611 | 18.186 | 16.954 | 16.954 | -0.022 |
| T38-T39 | 9.761 | 10.524 | 0.576 | 11.648 | 10.336 | 10.331 | 0.569 |
| T39-T40 | 2.051 | 2.815 | 0.614 | 4.017 | 2.052 | 2.046 | -0.004 |
| T40-T41 | 40.528 | 40.742 | 0.536 | 41.692 | 40.576 | 40.576 | 0.048 |
| T41-E3 | 6.444 | 7.280 | 0.760 | 8.839 | 8.149 | 8.141 | 1.697 |
| E3-T42 | 1.273 | 2.955 | 0.127 | 3.174 | 2.814 | 2.808 | 1.535 |
| T42-T43 | 4.006 | 4.722 | 1.289 | 7.256 | 3.841 | | *-0.165* |
| T43-T44 | 1.074 | 1.908 | 0.620 | 3.156 | | | |

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

**Table 9. Maneuver Cancellation Summary** these are comments

| Maneuver | Type | Location | Type | Magnitude | Cost to Cancel |
|---|---|---|---|---|---|
| OTM-122 | cleanup | T35-40d | RCS | 0.057 m/s | 0.457 m/s |
| OTM-123[a] | shaping | T35-25d | MEA | 0.398 m/s | 0.072 m/s |
| OTM-124 | approach | T35-3d | RCS | 0.060 m/s | 0.077 m/s |
| OTM-127 | cleanup | I1-2d | RCS | 0.025 m/s | 0.017 m/s |
| OTM-140 | cleanup | T40-13d | RCS | 0.000 m/s | 0.001 m/s |
| OTM-142 | approach | T40-3d | RCS | 0.031 m/s | -0.183 m/s |
| OTM-148 | approach | E3-3d | RCS | 0.007 m/s | -0.042 m/s |
| OTM-148-BU | approach | E3-2d | RCS | 0.014 m/s | -0.044 m/s |
| OTM-151 | approach | T42-3d | RCS | 0.004 m/s | -0.041 m/s |
| OTM-154[b] | approach | T43-3d | RCS | 0.015 m/s | 0.061 m/s |
| OTM-157 | approach | T44-3d | RCS | 0.002 m/s | -0.067 m/s |
| OTM-158 | cleanup | T45-60d | RCS | 0.052 m/s | -0.064 m/s |

[a]Backup location was used, $\Delta\mathbf{V}$ cost is for using the backup location
[b]Magnitude includes proposed biasing

verified that their observations will not be impacted by cancellation. As OTM-148 was in a leg that lead up to an Enceladus flyby (E3), removing the $\Delta\mathbf{V}$ perturbation to the trajectory was a notable benefit to OD for supporting the OTM-149 design and for the eventual reconstruction of the E3 flyby.

For OTM-149, the nominal strategy was to target straight to T42 so that OTM-150 would be nominally zero. Otherwise, OTM-150 would've had a deterministic part of 1 mm/s. Since OTM-150 was a shaping maneuver, it would target T42, anyway, and OTM-151 would not have a deterministic component. When it came time to execute OTM-150, analysis showed that canceling OTM-150 (5 mm/s) would give a deterministic part to OTM-151 five times the size of OTM-150 and the overall cost through T45 would be 0.34 m/s. This cost was apparently related to an increased deviation in T42's outgoing asymptote. So, the project decided to execute OTM-150, anticipating cancellation of OTM-151. As it turned out, OTM-151 was too small to execute at 4 mm/s. Fortunately, the $\Delta\mathbf{V}$ cost of cancellation showed an improvement and there was no penalty to the science return.

The decision for canceling OTM-154 was more complicated. The issue under consideration was what impact the cancellation of OTM-154 would have on the probability of cancellation on OTM-157, the T44 approach maneuver. See Section IX. Being an approach maneuver, OTM-157's $\Delta\mathbf{V}$ magnitude would be strongly determined by execution errors from OTM-156. So, to decide cancellation of OTM-157, the $\Delta\mathbf{V}$ magnitude of OTM-156 needed to be investigated.

Comparing the predicted magnitude of OTM-156 with and without OTM-154 indicated that the deterministic $\Delta\mathbf{V}$ increased from about 0.2 m/s to 0.3 m/s. Such a small deterministic part would give way to other factors, such as errors in the Titan flyby, to determine the $\Delta\mathbf{V}$ magnitude. As such, OTM-154 was cancelled without significantally impacting the probability of OTM-157 cancellation.

As intended, OTM-157 was canceled. It had an estimated magnitude of only 2 mm/s and the error it would've corrected in the B-plane was only 400 meters. Such fortuitous results were due significantly to the accurate OD estimation and execution errors of OTM-156.

## VI. Deleted Maneuvers

In many cases during the past four years, maneuvers could be cancelled significantly in advance of their execution. Such a cancellation in advance is referred to here as a deletion. The analysis for a deletion is very similar to that for cancellation. During this fourth year of the tour, two maneuvers were deleted, OTM-120 and OTM-126.

OTM-120 was a trajectory-shaping maneuver. The $\Delta\mathbf{V}$ cost of deleting OTM-120 was estimated to be about 40 mm/sec and the major benefit was the removal of many spacecraft and navigation activities during the weekend following the July 4th holiday. In addition, this improved the OD accuracy leading to OTM-121. Note that this cancellation meant that OTM-119, a clean-up maneuver, was targeted directly to the T34

aimpoint instead of using the optimization strategy.

OTM-126 was deleted once the maneuver team showed that there was virtually no difference between the trajectory to Iapetus with or without the maneuver. Further, the prediction was that OTM-126 would be very small and might have to be cancelled for being too small to execute. There was no mission $\Delta\mathbf{V}$ penalty associated with deleting OTM-126. The OD showed a large uncertainty and the consensus was that even with large changes in the OD predictions, the $\Delta\mathbf{V}$ penalty would not increase significantly.

## VII. Maneuvers Not Cancelled

Some maneuvers during the tour which were small also had the paradoxical feature of not being cancelable. This was due to either mission constraints, high downstream $\Delta\mathbf{V}$ costs, or the desire to cancel a different maneuver.

OTM-130 was small but not cancelled because the flyby altitude at T34 could've gone too low. The guideline established by the project is that Navigation should control the flyby altitude so that the 2-$\sigma$ estimate of flyby altitude at Titan would be greater than 960 km. If the flyby altitude had been acceptable, cancelling OTM-130 would've saved 0.17 m/s.

OTM-150 was not cancelled so that OTM-151 could be cancelled for a smaller cost, see Section V.

Most notably, the maneuvers supporting T37, T38, and T39 went by without cancellation. These were OTMs 131 through 139. OTM-133 was small but could not be cancelled. In the B-plane, the correction need was about 12 km; if uncorrected, the declination of the outgoing asymptote would be misaligned by 0.6 mrad and would require a 3 m/s correction at OTM-134. OTM-135 would be slightly reduced, but the overall downstream $\Delta\mathbf{V}$ cost of 2.5 m/s was still too large. The situation for OTM-136 was very similar to that for OTM-133. Cancelling OTM-136 would cause OTM-137 to increase by 2 m/s and the overall cost of 1.4 m/s was too large. As before, the culprit appears to have been the change in the declination of the hyperbolic orbit's outgoing asymptote, 0.4 mrad. Analysis for cancelling OTM-139 showed that the overall downstream $\Delta\mathbf{V}$ cost was high, 2 m/s, but, unlike the previous two situations, that cost was spread more evenly amongst downstream encounters. Half of the cost was at OTM-140, most of the other half was targeting the next encounter, T41, and the remaining 10% was the encounter after next, Enceladus-3 (E3). Note, also, that once the asymptote's declination was taken care of with OTM-139, OTM-140 was cancelled with a cost of a mere 1 mm/s, see Table 9

Those three maneuvers, OTMs 133, 136, and 139, were the approach maneuvers for the encounters that provided the largest changes in inclination, see Figure 2. In each case, canceling what appeared to be a small maneuver would've left a deviation in the declination of the outgoing asymptote, strongly related to inclination, that would be expensive to correct with a maneuver 3 days after the encounter. Recalling that the encounters are at the orbit's node, this is consistent with how difficult an inclination change would be via $\Delta\mathbf{V}$ away from the orbit's node.

In general, when a maneuver design was less than 9 mm/s but couldn't be canceled, target biasing was considered. Previously,[7] this criteria was 10 mm/s, but it has been lowered as the ground system has gained greater confidence in executing small maneuvers. The targeting parameter chosen to be biased in every case was the time of closest approach.

The required bias is estimated by a linear model of the maneuver, $\Delta V = \mathbf{K}\Delta B$. Holding $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ fixed, the $\Delta\mathbf{V}$ magnitude becomes a quadratic equation in terms of time-of-flight where two solutions exist for a desired $\Delta\mathbf{V}$ value.[7] Generally, the smaller bias is chosen to adjust the maneuver's aimpoint.

As noted in Tables 4 and 9, the aimpoint for OTM-121 (T34 flyby) and the aimpoint for OTM-154 (T43 flyby) were biased. The designs for OTM-154 were indicating a very small maneuver, about 5 mm/s. The target was preliminarily biased by about 0.4 sec to increase the maneuver to 15 mm/s. However, it was eventually cancelled, see Section V.

OTM-121 also came to have a very small $\Delta\mathbf{V}$ magnitude. This small magnitude was due to the accuracy of OTM-119, which took place on July 2, 2007. OTM-119 was a cleanup maneuver but, because OTM-120 was deleted, it was targeted directly to the T34 aimpoint. OTM-121 was too small to implement but canceling the maneuver would have built-in a 1 m/s cost. Given the large cost and the Science team's desire for an accurate flyby, the project decided to bias the target time. The shift in target time was determined by increasing the maneuver to 12.5 mm/s. The figure of 12.5 mm/s was the sum of 4.5 mm/s for AACS events, 6 mm/s for a minimum maneuver size, and an extra 2 mm/s per engineering judgement. The shift in target time was determined to be 0.39 seconds, giving the new T34 target epoch of 19-JUL-2007 01:12:25.39 ET.

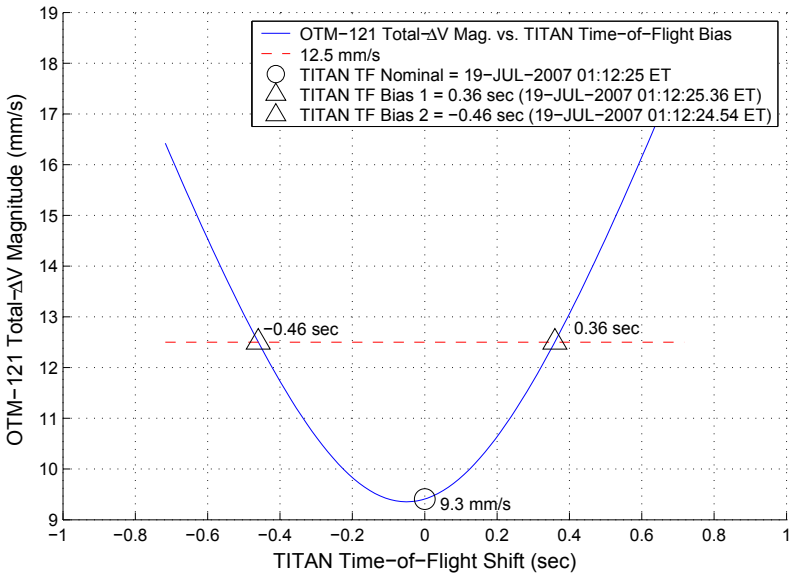


**Figure 6. Time-of-Flight Bias for OTM-121** The plot shows a 0.36 sec shift instead of a 0.39 sec shift because the computation depicted was only accurate to 1st-order variations in $\Delta\mathbf{V}$.

## VIII. Backup Locations

A backup location is paired with the prime location for every maneuver in the mission. The backup location's purpose is to protect against Deep Space Network (DSN) uplink issues. The backup is typically located one day after the prime location. In the vast majority of cases, the backup has not been used. It was almost used for OTM-148 and it was used for OTM-123.

The backup location for OTM-123 was used when the DSN was unable to support the uplink for the nominal maneuver location. The total downstream cost up to T38 was 0.07 m/s (primarily due to 0.033 m/s more for OTM-123-BU and 0.036 m/s for OTM-125). A positive outcome was that the additional cost drove OTM-125 up to a magnitude consistent with the MEA instead of the RCS thrusters, thus reducing the use of the more limited hydrazine.

For quite a different reason, the prime OTM-148 location was put aside. OTM-148 was the approach maneuver for the Enceladus-3 flyby. In the days leading up to this maneuver, a picture of Enceladus was to be used for Optical Navigation. Unfortunately, that opportunity was missed. It was regained the next day at the expense of the OTM-148 location. Interestingly, only about 14 mm/s would be required of OTM-148-BU – in fact, it was cancelled to reqp a savings of about 44 mm/s, see Table 9. Cancellation also eliminated a perturbation to the trajectory so as to improve the OD solution in support of the OTM-149 design and reconstruction of the E3 flyby.

## IX. Special Cases

OTM-146 represents an unusual class of optimization results for this mission where the cleanup maneuver bore the largest portion of the $\Delta\mathbf{V}$ at about 7 m/s, see Tables 6-7. On the other hand, OTM-147, the shaping maneuver, which is the larger of the two in most cases, was only about 1 m/s. OTM-146 also was distinctive in that the $\Delta\mathbf{V}$ cost of the backup maneuver location was quite high; OTM-146-BU was 22.5 m/s which also would've increased OTM-147 to about 5 m/s. The overall cost, including downstream maneuvers, came to about 23 m/s. To decrease the likelihood of using the backup location[f], the project opted for an early uplink of the maneuver so that more there were more opportunities to retry the uplink before the backup location would be required.

The largest part of the discussion during the OTM-155 design process was about the cancellation potential of OTM-157. OTM-157 had been moved to accommodate Phoenix[18,19] landing operations. The new location

[f]The maneuver backup locations are intended to protect against DSN uplink issues.

was close enough to OTM-156 that it was undesirable, from an operations perspective, to execute OTM-157. Furthermore, the OTM-157-BU had to be scheduled on Memorial Day. The project explored the option of targeting OTM-155 directly to the T44 encounter which would eliminate the deterministic component of OTM-156 and allow it to function purely to cleanup OTM-155 execution errors. However, that doubled the size of OTM-155, making it 2 m/s in addition to causing much larger trajectory deviations downstream (T44-T45). Instead, the nominal strategy was held, OTM-156 remained at 0.2 m/s, and its execution was accurate enough that OTM-157 could be cancelled.

### IX.A. OTM-159 Backup Location Study

OTM-159 was the subject of navigation's analysis because its backup location incurred much more $\Delta\mathbf{V}$, 32 m/s, than its nominal location with 12 m/s. Of larger concern, the downstream cost of using the backup location was about 97 m/s as seen in Table 10. Other options were investigated that involved altering downstream encounters to absorb the $\Delta\mathbf{V}$. The most promising strategy moved OTM-159-BU by a week, reducing it to 19 m/s, eliminating an Enceladus flyby (E6), and altering Titan flbys from T45 to T51. See Table 10. With that effort, the cost of using the backup location would be 8 m/s. To reduce the likelihood of invoking such measures, an earlier uplink window for OTM-159 was used. Both the uplink and execution of the maneuver were nominal.

**Table 10. OTM-159 Backup Location Study** Total $\Delta\mathbf{V}$ is for OTMs 159-255 "Float" means to allow flyby time, periapsis radius, and B-plane angle to change within a certain range

| | Nominal Tour | Nominal Tour with OTM-159 at BU location | Case 1: OTM-159 at BU location | Case 2: OTM-159 one DSN track later | Case 3: OTM-159 after next periapses | Case 4: OTM-159 after next periapses |
|---|---|---|---|---|---|---|
| OTM-159 | 23-JUN-2008 06:25:05 ET $\Delta\mathbf{V}$ = 12 m/s | 23-JUN-2008 15:25:05 ET $\Delta\mathbf{V}$ = 32 m/s | 23-JUN-2008 15:25:05 ET $\Delta\mathbf{V}$ = 32 m/s | 25-JUN-2008 00:00:00 ET $\Delta\mathbf{V}$ = 111 m/s | 30-JUN-2008 16:00:00 ET $\Delta\mathbf{V}$ = 19 m/s | 30-JUN-2008 16:00:00 ET $\Delta\mathbf{V}$ = 19 m/s |
| Comments | | •BU location 9 hours after prime location •Maintains ref traj flyby conditions | •No E6 -Float* T45, T49, T50 | •No E6 •Float* T45, T49, T50 | •Not on existing DSN track •No E6 -Float* T45, T46,T47,T49, T50,T51 | •Not on existing DSN track •No E6 •Float* T45, T49, T50,T51 •Two-piece file |
| T45 altitude | 1613.4 km | 1613.4 km | 1667.56 km | 2103.48 km | 1784.26 km | 1791 km |
| Total $\Delta\mathbf{V}$ | **186.04 m/s** | 283.53 m/s | 207.26 m/s | 286.99 m/s | **194.33 m/s** | 198 m/s |
| Cost | 0 m/s | 97.49 m/s | 21.22 m/s | 100.95 m/s | 8.29 m/s | 12 m/s |

### IX.B. Enceladus Plume Occultation

OTM-128 was the cleanup maneuver after Iapetus-1. The encounter after Iapetus-1 was T36 for which OTM-131 was the cleanup maneuver. OTM-131 was a special case because it targeted an Enceladus for a plume occultation. The Enceladus plume occultation (aka Enceladus star occultation) was a key piece of the decision making process for OTM-128. The geometry of this occultation is shown in Figure 7. Six options were investigated:

1. Perform OTM-128 as a stand-alone maneuver which would target the T36 Titan encounter directly with OTM-131 targeting the Enceladus star occultation directly.

2. Perform OTM-128 as a stand-alone maneuver which targeted the T36 Titan encounter directly with OTM-131 targeting a 'floating point' (not the Enceladus star occultation).

3. Perform OTM-129 as a stand-alone maneuver (thus cancelling OTM-128) which would target the T36 Titan encounter directly with OTM-131 targeting the Enceladus star occultation directly.

4. Perform OTM-129 as a stand-alone maneuver which would target the T36 Titan encounter directly with OTM-131 targeting a 'floating point'.

5. Perform OTM-128 and OTM-129 in the nominal optimized setup which would target the T36 Titan encounter and target OTM-131 to the Enceladus star occultation directly.

6. Perform OTM-128 and OTM-129 in the nominal optimized setup which would target the T36 Titan encounter and target with OTM-131 to a 'floating point'.

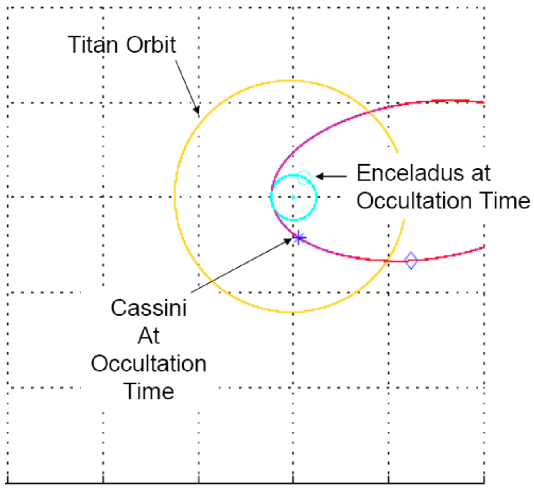


**Figure 7. Trajectory plot for Enceladus Plume Occutation** View is looking down from Saturn's North pole. Titan's orbit is orange, Enceladus' orbit is blue.

A study had been performed[20] showing the delivery accuracy at the time of the occultation depending on whether the occultation time was targeted directly or the 'floating point' target was used. Not targeting the occultation produced a 1-$\sigma$ position ellipsoid with semiaxes of (654, 262, 78) km in Saturn Equator of Date coordinates ($x$, $y$, and $z$, respectively). Directly targeting the occultation produced semiaxes of (80, 25, 2) km but most of this deviation came from the OD uncertainty which had semiaxes of (59, 18, 1) km. The $\Delta\mathbf{V}$ cost to target the Enceladus star occultation directly was approximately 1.3 m/s which would affect the magnitudes of only OTM-131 and OTM-132.

The comparisons of the six cases are shown in Table 11, which contains the cumulative $\Delta\mathbf{V}$s from the I1 encounter to the T39 encounter. There would be very little difference between performing OTM-128 only, OTM-129 only, or OTM-128 and OTM-129 if the Enceladus Occultation was not targeted. But, the table shows that there would be a substantial $\Delta\mathbf{V}$ penalty of 3.58 m/s if OTM-128 were cancelled and only OTM-129 performed. Additionally considering trajectory deviations, the decision was to target OTM-128 directly to the T36 encounter which would make OTM-129 a statistical maneuver and target OTM-131 to the Enceladus star occultation directly. Unfortunately, just after the Iapetus encounter (I1), the spacecraft went into safe mode and OTM-129 was needed to target to T36. The Enceladus plume occultation was not affected.

**Table 11. Results for OTM-128 and OTM-129** Targeting options for the Enceladus plume occultation.

| | OTM-128 only | OTM-129 only | OTM-128 and OTM-129 |
|---|---|---|---|
| OTM-131 targets occul. | 42.53 m/s | 45.39 m/s | 42.54 m/s |
| OTM-131 targets floating pt. | 41.89 m/s | 41.81 m/s | 41.89 m/s |
| Difference | 0.64 m/s | 3.58 m/s | 0.65 m/s |

## X. Closing

Of the 42 maneuvers planned during the fourth year of the Saturn tour, 29 maneuvers were per- formed in the prime locations; one maneuver was executed in the back-up location; 10 maneuvers were cancelled; and 2 maneuver were deleted. Twenty (20) maneuvers were performed with the MEA, while 10 utilized the RCS. One maneuver was executed with a biased time-of-flight target. Through the whole year, the $\Delta\mathbf{V}$ cost due to navigation was below 2 m/s per encounter and it the vast majority of cases was less than 0.5 m/s per encounter.

In the last year of its prime mission at Saturn, the Cassini orbiter has been navigated successfully, in great part due to the excellent maneuver performance of the spacecraft. The team fully expects this success to continue and should help enable exciting science investigations of the Saturn planetary system in the Cassini Equinox Mission.[15]

## Appendix

### B-plane Description

Planet or satellite targeting is described in aiming plane coordinates referred to as *B-plane* coordinates[12] (Fig. 8). The B-plane is a plane passing through the body center and perpendicular to the asymptote of the incoming trajectory (assuming 2 body conic motion). The "B-vector", **B**, is a vector in that plane, from body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the body had no mass and did not deflect the flight path. Coordinates are defined along three orthogonal unit vectors, **S**, **T**, and **R** with the system origin at the body center. The **S** vector is parallel to the spacecraft $V_\infty$vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). **T** is parallel to a convenient reference plane, and **R** completes an orthogonal triad with **S** and **T**. The reference plane for the **T** vector is generally the ecliptic plane (EMO2000). For Titan equator of date, the reference plane is in Titan's equatorial plane at the given epoch. With **S**, **T**, and **R** thus defined, a target point can be described in terms of the B-vector dotted into the **R** and **T** vectors ($\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$), or as the magnitude of **B** and the angle $\phi$ clockwise from **T** to **B**.

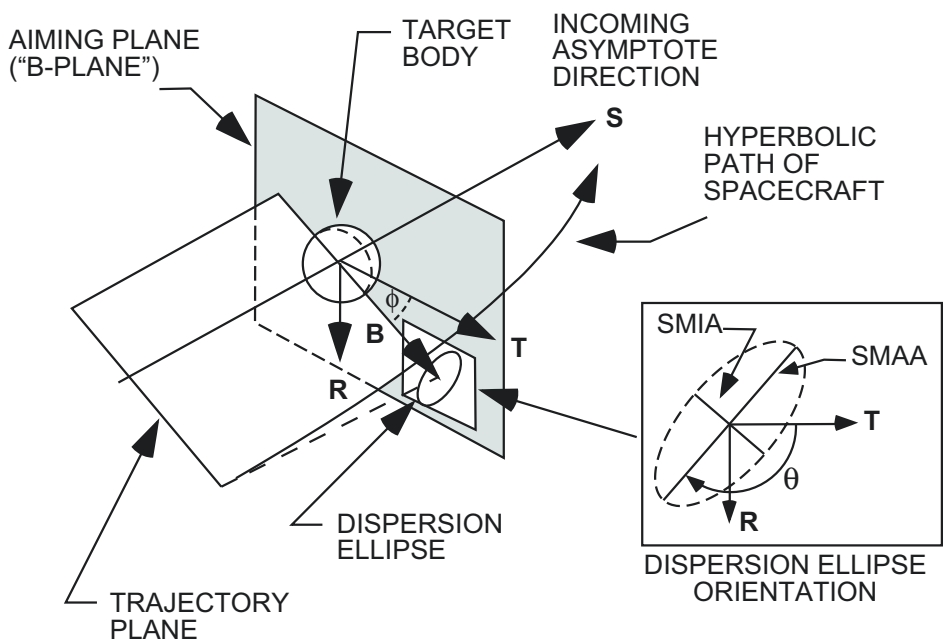


**Figure 8. B-Plane Coordinate System.**

Trajectory errors in the B-plane are often characterized by a one-$\sigma$ dispersion ellipse, shown in Fig. 8. SMAA and SMIA denote the semi-major and semi-minor axes of the ellipse; $\theta$ is the angle measured clockwise from the **T** axis to SMAA. The dispersion normal to the B-plane is typically given as a one-$\sigma$ time-of-flight

error, where time-of-flight specifies what the time to swingby (periapsis) would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, this dispersion is sometimes given as a one-$\sigma$ distance error along the **S** direction, numerically equal to the time-of-flight error multiplied by the magnitude of the $V_\infty$ vector.

## Acknowledgments

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

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