# Cassini Tour Navigation Strategy

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## BIOGRAPHY

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## ABSTRACT

The Cassini-Huygens spacecraft was launched on October 15, 1997 as a joint NASA/ESA mission to explore Saturn. After a 7 year cruise the spacecraft will enter orbit around Saturn on 1 July 2004 for a 4 year investigation of the Saturnian system. The Cassini Navigation Team is responsible for designing the reference trajectory and conducting operations to realize this design. This paper describes the strategy for achieving project requirements, the characteristics of the Cassini navigation challenge, and the underlying assumptions.

## INTRODUCTION

The Cassini-Huygens spacecraft was launched October 15, 1997 and is currently en route to Saturn, having completed flybys of Venus, Earth, and Jupiter. On July 1, 2004, after becoming the first spacecraft captured into orbit around Saturn, Cassini will begin a four year tour of the Saturnian system, where it will study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites. The Cassini orbiter carries the Huygens probe, which will be the first spacecraft to land on Saturn's moon Titan. Both Cassini and Huygens will study Titan's atmospheric structure and composition as well as Titan's surface topography.

During the tour, the Cassini navigation system supports both the updating of the nominal tour trajectory and the control of the spacecraft's trajectory on the nominal tour. The objective of updating the nominal tour trajectory will be to maintain the pre-planned sequence of encounters while accounting for expected variations in the major satellite ephemerides and, possibly, the Titan atmosphere model.

The tour navigation requires a mixture of radiometric tracking data (Doppler and ranging) and optical images of Titan and the other major Saturn satellites. During the tour the average number of optical navigation images starts at 3 per day at the beginning of the tour, decreases to 1.65 per day after the Tc Titan encounter, and decreases further to 0.5 per day after the T6 Titan encounter.

In addition to spacecraft ephemerides, the Navigation Team will also provide ephemerides for the major Saturnian satellites. Prior to Saturn approach, the ephemerides of the major Saturnian satellites will be known to a $1\sigma$ accuracy somewhere between 180 and 1700 km depending upon the satellite and the ground observation schedule. During the approach phase, the optical images will be used to reduce this uncertainty to less than 100 km. Once in the tour phase, the uncertainty will decrease to less than 10 kilometers. The major satellite ephemerides will be updated periodically and delivered to the project in order to maintain the needed accuracy level.

Given the nominal tour trajectory, the maneuver control strategy is to deliver the spacecraft to the targeted encounter condition specified in the current reference trajectory. Between each targeted encounter, three Orbit Trim Maneuvers (OTMs) are generally scheduled. A typical schedule places the first OTM about 3 days after the targeted encounter, the second near apoapsis, and the third maneuver 3 days before the next targeted encounter. There are numerous exceptions to this general scheme.

A multi-impulse chained targeting strategy will be used to achieve the targeted encounter conditions with a minimum of $\Delta V$. This strategy, discussed later in more detail, optimizes the post encounter and apoapsis maneuvers together on up to 5 legs of the tour to find a minimum $\Delta V$. As a result of this strategy, the spacecraft trajectory does not, in general, achieve the desired flyby conditions until after the apoapsis maneuver.

## TRAJECTORY DESIGN

The four year tour of the Saturnian system starts after the Saturn orbit insertion (SOI) maneuver. After SOI, the orbit periapsis is raised by a large maneuver (PRM) to set up the first targeted flyby of Titan. After the second Titan flyby, the entire spacecraft is put on course to the Huygens Probe entry interface point on the 3rd Titan flyby (Tc). Once the probe has been released, the Orbiter trajectory is deflected to set up a high altitude flyby of Titan to record the Probe data. Then the post-Huygens tour starts. Flyby epochs, altitudes, etc., are summarized in Table 1. Table 2 lists the non-targeted icy satellite encounters under 100,000 km altitude.

The Cassini tour is the most complex gravity-assist tour yet flown. It balances many competing science objectives to explore the Saturnian system. The current tour design, T2003-01[1,2,3,4], consists of 45 targeted flybys of Titan and 7 targeted icy satellite flybys. During different phases of the tour, different science objectives dominate the tour design. Some science objectives require orbit geometries that are time sensitive and other objectives require geometries that take several flybys to achieve. The Cassini tour design arranges these geometries so that they may be accomplished in a four year mission. The various phases of the Cassini tour are shown in Figure 1 as a plot of inclination versus time.

The Cassini tour is composed of three kinds of Titan-to-Titan transfers: resonant transfers, pi-transfers, and non-resonant transfers. A resonant transfer encounters Titan at the same place in its orbit (i.e. there are multiples of 360° between encounters). For resonant transfers, the flight time between Titan encounters is an integer multiple of Titan's period (i.e., Cassini's orbit is resonant with Titan's orbit). When a Titan-to-Titan transfer occurs with 180° plus some multiple of 360° between Titan encounters it is called a pi-transfer or a 180° transfer (this type of transfer is also often referred to as a back-flip transfer). Pi-transfers are usually highly inclined[5] and require many additional flybys to set up the required geometry. Transfers that encounter Titan with an arbitrary (i.e. not multiples of 180°) angle between encounters are referred to as non-resonant transfers.

When the spacecraft's orbit is inclined, it may only encounter Titan on the line where its orbit plane intersects Titan's orbit plane. Thus, the spacecraft must use a resonant or pi-transfer. However, when Cassini's orbit plane is close to Titan's orbit plane, non-resonant transfers are possible so long as the phasing between Cassini and Titan is such that Titan will be in the right place when Cassini crosses its orbit.

Saturn's icy satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus, and Phoebe) are not large enough to be used for gravity-assists. Therefore, icy satellite flybys are targeted by designing a Titan-to-Titan transfer that passes close to the desired icy satellite. Maneuvers are then used to target the desired flyby conditions.

## PROBE MISSION (TA-T3)

The Huygens probe is to be delivered on the Tc flyby. The Ta, Tb, and Tc flyby sequence is the result of the Huygens Recovery Task Force (HRTF) efforts to redesign the probe mission to recover from an anomaly in the Huygens relay link[6,7,8]. Cassini arrives at Saturn with a 17° inclination, and this sequence reduces that inclination to 0.3° to set up the needed geometry for the T3-T4 non-resonant transfer and the E1 Enceladus flyby.

## OCCULTATIONS / ICY SATELLITES (T3-T9)

Four icy satellite flybys as well as important occultations of Saturn occur during this phase of the tour. The first icy satellite flyby of the tour, E1, occurs between the T3 and T4 flybys. The T4 and T5 flybys then raise the inclination to ~22° to set up the orbit geometry needed for seven radio science near-equatorial occultations of Saturn and its rings between the T5 and T6 flybys (Figure 2). Such occultation passes are only possible in the beginning of the mission because by the end of the mission Saturn's rings are edge on as seen from Earth. The second Enceladus encounter (E2) occurs during the T5-T6 transfer. T6 and T7 then lower the inclination back into Titan's orbit plane for flybys of Hyperion (H1) and Dione (D1) on the non-resonant T7-T8 transfer and a flyby of Rhea (R1) between T8 and T9. The non-resonant T7-T8 and T8-T9 transfers also begin to rotate Cassini's apoapsis towards Saturn's magnetotail.

## MAGNETOTAIL PASSAGE (T9-T16)

During this phase of the mission, non-resonant transfers are used to move the apoapsis of Cassini's orbit behind Saturn as seen from the Sun with the goal of moving Cassini into Saturn's magnetotail. In this phase, Titan flybys alternate between inbound (i.e. before Saturnian periapsis) and outbound (i.e. after periapsis) encounters. This is done in such a way as to rotate the apoapsis as quickly as possible into the magnetotail[1,2,5]. At the end of this phase the Cassini apoapsis is in the anti-sun direction and the T16 flyby increases the inclination to ~15° to pass through Saturn's magnetotail.

**Table 1: THE CASSINI TOUR (T2003-01)[a]**

| Encounter | Satellite | Time (UTC) | TOF [days] | In / Out | Altitude [km] | B-Plane [deg] | V-Infinity [km/s] | Period [days] | Inc. [deg] | Rev |
|---|---|---|---|---|---|---|---|---|---|---|
| Ta | Titan | 26-Oct-04 15:30 | 118 | I | 1200 | -39 | 5.65 | 47.8 | 13.8 | a |
| Tb | Titan | 13-Dec-04 11:37 | 165 | I | 2336 | -49 | 5.65 | 32.0 | 8.5 | b |
| Tc | Titan | 14-Jan-05 11:05 | 197 | I | 60000 | 180 | 5.38 | 33.3 | 8.6 | c |
| T3 | Titan | 15-Feb-05 06:54 | 229 | I | 950 | -43 | 5.58 | 20.5 | 0.3 | 3 |
| E1 | Enceladus | 09-Mar-05 09:07 | 251 | I | 500 | 150 | 6.61 | 20.5 | 0.4 | 4 |
| T4 | Titan | 31-Mar-05 19:55 | 274 | O | 2523 | -148 | 5.61 | 16.0 | 7.0 | 5 |
| T5 | Titan | 16-Apr-05 19:06 | 290 | O | 950 | -76 | 5.63 | 18.1 | 21.6 | 6 |
| E2 | Enceladus | 14-Jul-05 19:57 | 379 | I | 1000 | -160 | 8.12 | 18.3 | 21.8 | 11 |
| T6 | Titan | 22-Aug-05 08:40 | 417 | O | 4015 | 122 | 5.60 | 16.0 | 16.1 | 13 |
| T7 | Titan | 07-Sep-05 07:50 | 433 | O | 950 | 68 | 5.63 | 18.4 | 0.3 | 14 |
| H1 | Hyperion | 26-Sep-05 01:41 | 452 | O | 1000 | 180 | 5.62 | 18.2 | 0.3 | 15 |
| D1 | Dione | 11-Oct-05 17:58 | 468 | I | 500 | 120 | 9.03 | 17.9 | 0.4 | 16 |
| T8 | Titan | 28-Oct-05 03:58 | 484 | I | 1446 | 181 | 5.52 | 30.3 | 0.4 | 17 |
| R1 | Rhea | 26-Nov-05 22:36 | 514 | I | 500 | 10 | 7.28 | 27.4 | 0.4 | 18 |
| T9 | Titan | 26-Dec-05 18:55 | 544 | O | 10429 | 180 | 5.49 | 23.4 | 0.4 | 19 |
| T10 | Titan | 15-Jan-06 11:36 | 563 | I | 2042 | 180 | 5.48 | 39.2 | 0.4 | 20 |
| T11 | Titan | 27-Feb-06 08:21 | 606 | O | 1812 | 180 | 5.51 | 23.3 | 0.4 | 21 |
| T12 | Titan | 18-Mar-06 23:58 | 626 | I | 1947 | 180 | 5.48 | 39.2 | 0.4 | 22 |
| T13 | Titan | 30-Apr-06 20:54 | 669 | O | 1853 | 180 | 5.49 | 23.3 | 0.4 | 23 |
| T14 | Titan | 20-May-06 12:13 | 688 | I | 1879 | 180 | 5.48 | 39.2 | 0.4 | 24 |
| T15 | Titan | 02-Jul-06 09:12 | 731 | O | 1911 | 179 | 5.48 | 23.3 | 0.4 | 25 |
| T16 | Titan | 22-Jul-06 00:25 | 751 | I | 950 | -92 | 5.52 | 24.0 | 14.9 | 26 |
| T17 | Titan | 07-Sep-06 20:12 | 799 | I | 950 | -24 | 5.54 | 16.0 | 24.7 | 28 |
| T18 | Titan | 23-Sep-06 18:53 | 815 | I | 950 | -81 | 5.54 | 16.0 | 37.7 | 29 |
| T19 | Titan | 09-Oct-06 17:23 | 831 | I | 950 | -75 | 5.54 | 16.0 | 46.8 | 30 |
| T20 | Titan | 25-Oct-06 15:51 | 847 | I | 950 | -11 | 5.55 | 12.0 | 55.4 | 31 |
| T21 | Titan | 12-Dec-06 11:35 | 894 | I | 950 | -121 | 5.53 | 16.0 | 53.3 | 35 |
| T22 | Titan | 28-Dec-06 10:00 | 910 | I | 1500 | -61 | 5.54 | 16.0 | 56.8 | 36 |
| T23 | Titan | 13-Jan-07 08:34 | 926 | I | 950 | -52 | 5.54 | 16.0 | 59.4 | 37 |
| T24 | Titan | 29-Jan-07 07:12 | 942 | I | 2776 | -69 | 5.54 | 18.1 | 59.0 | 38 |
| T25 | Titan | 22-Feb-07 03:11 | 966 | O | 953 | -55 | 5.83 | 16.0 | 58.8 | 39 |
| T26 | Titan | 10-Mar-07 01:47 | 982 | O | 956 | -48 | 5.83 | 16.0 | 56.2 | 40 |
| T27 | Titan | 26-Mar-07 00:22 | 998 | O | 953 | -58 | 5.83 | 16.0 | 52.4 | 41 |
| T28 | Titan | 10-Apr-07 22:57 | 1014 | O | 951 | -66 | 5.83 | 16.0 | 46.9 | 42 |
| T29 | Titan | 26-Apr-07 21:33 | 1030 | O | 951 | -73 | 5.83 | 16.0 | 39.0 | 43 |
| T30 | Titan | 12-May-07 20:08 | 1046 | O | 950 | -79 | 5.83 | 16.0 | 28.0 | 44 |
| T31 | Titan | 28-May-07 18:51 | 1062 | O | 2425 | -84 | 5.83 | 16.0 | 18.0 | 45 |
| T32 | Titan | 13-Jun-07 17:47 | 1078 | O | 950 | -87 | 5.83 | 16.0 | 19.5 | 46 |
| T33 | Titan | 29-Jun-07 17:05 | 1094 | O | 1942 | -8 | 5.86 | 22.8 | 0.4 | 47 |
| T34 | Titan | 19-Jul-07 00:40 | 1113 | I | 1302 | -179 | 5.86 | 39.7 | 0.3 | 48 |
| T35 | Titan | 31-Aug-07 06:34 | 1156 | O | 3227 | -116 | 5.84 | 32.4 | 6.5 | 49 |
| I1 | Iapetus | 10-Sep-07 12:34 | 1166 | O | 1000 | 159 | 2.36 | 32.0 | 6.2 | 49 |
| T36 | Titan | 02-Oct-07 04:49 | 1188 | O | 950 | 120 | 5.90 | 23.8 | 5.0 | 50 |
| T37 | Titan | 19-Nov-07 00:53 | 1236 | O | 950 | 157 | 5.90 | 16.0 | 12.4 | 52 |
| T38 | Titan | 05-Dec-07 00:06 | 1252 | O | 1300 | 96 | 5.92 | 16.0 | 26.4 | 53 |
| T39 | Titan | 20-Dec-07 22:57 | 1268 | O | 953 | 101 | 5.92 | 16.0 | 38.0 | 54 |
| T40 | Titan | 05-Jan-08 21:26 | 1284 | O | 949 | 166 | 5.91 | 11.9 | 47.1 | 55 |
| T41 | Titan | 22-Feb-08 17:39 | 1332 | O | 959 | 140 | 5.95 | 10.6 | 56.8 | 59 |
| E3 | Enceladus | 12-Mar-08 19:06 | 1351 | I | 1000 | 0 | 14.59 | 10.6 | 56.8 | 61 |
| T42 | Titan | 25-Mar-08 14:35 | 1364 | O | 950 | 147 | 5.96 | 9.6 | 63.7 | 62 |
| T43 | Titan | 12-May-08 10:10 | 1411 | O | 950 | -162 | 5.95 | 8.0 | 70.1 | 67 |
| T44 | Titan | 28-May-08 08:33 | 1427 | O | 1316 | -168 | 5.95 | 7.1 | 75.6 | 69 |

[a]TOF = time of flight from SOI start. In/Out = flyby inbound (I) or outbound (O). B-plane = B-plane angle relative to the satellite's pole (H1 angle is relative to Saturn pole). Period = spacecraft period after encounter. Inc. = inclination after encounter. Rev = spacecraft revolution # of flyby.

**Table 2: NON-TARGETED ENCOUNTERS**

| Satellite | Date | Altitude | Rev | Satellite | Date | Altitude | Rev |
|---|---|---|---|---|---|---|---|
| Mimas | 2004 JUL 01 | 76804 | 0 | Enceladus | 2006 NOV 09 | 94410 | 32 |
| Dione | 2004 DEC 15 | 81425 | b | Dione | 2006 NOV 21 | 72290 | 33 |
| Iapetus | 2005 JAN 01 | 63652 | c | Tethys | 2007 MAY 26 | 97130 | 45 |
| Enceladus | 2005 FEB 17 | 1180 | 3 | Tethys | 2007 JUN 27 | 16170 | 47 |
| Tethys | 2005 MAR 09 | 82980 | 4 | Mimas | 2007 JUN 27 | 89730 | 47 |
| Enceladus | 2005 MAR 29 | 63790 | 5 | Enceladus | 2007 JUN 28 | 90770 | 47 |
| Mimas | 2005 APR 15 | 77230 | 6 | Tethys | 2007 AUG 29 | 48320 | 49 |
| Tethys | 2005 MAY 02 | 64990 | 7 | Rhea | 2007 AUG 30 | 5100 | 49 |
| Enceladus | 2005 MAY 21 | 93000 | 8 | Dione | 2007 SEP 30 | 556520 | 50 |
| Mimas | 2005 AUG 02 | 45110 | 12 | Enceladus | 2007 SEP 30 | 88170 | 50 |
| Tethys | 2005 SEP 24 | 33300 | 15 | Rhea | 2007 NOV 16 | 78360 | 52 |
| Enceladus | 2005 OCT 12 | 42640 | 16 | Mimas | 2007 DEC 03 | 79270 | 53 |
| Enceladus | 2005 DEC 24 | 97170 | 19 | Mimas | 2008 APR 11 | 95430 | 64 |
| Rhea | 2006 MAR 21 | 85940 | 22 | Enceladus | 2008 JUN 30 | 99090 | 74 |
| Enceladus | 2006 SEP 09 | 39840 | 28 | | | | |

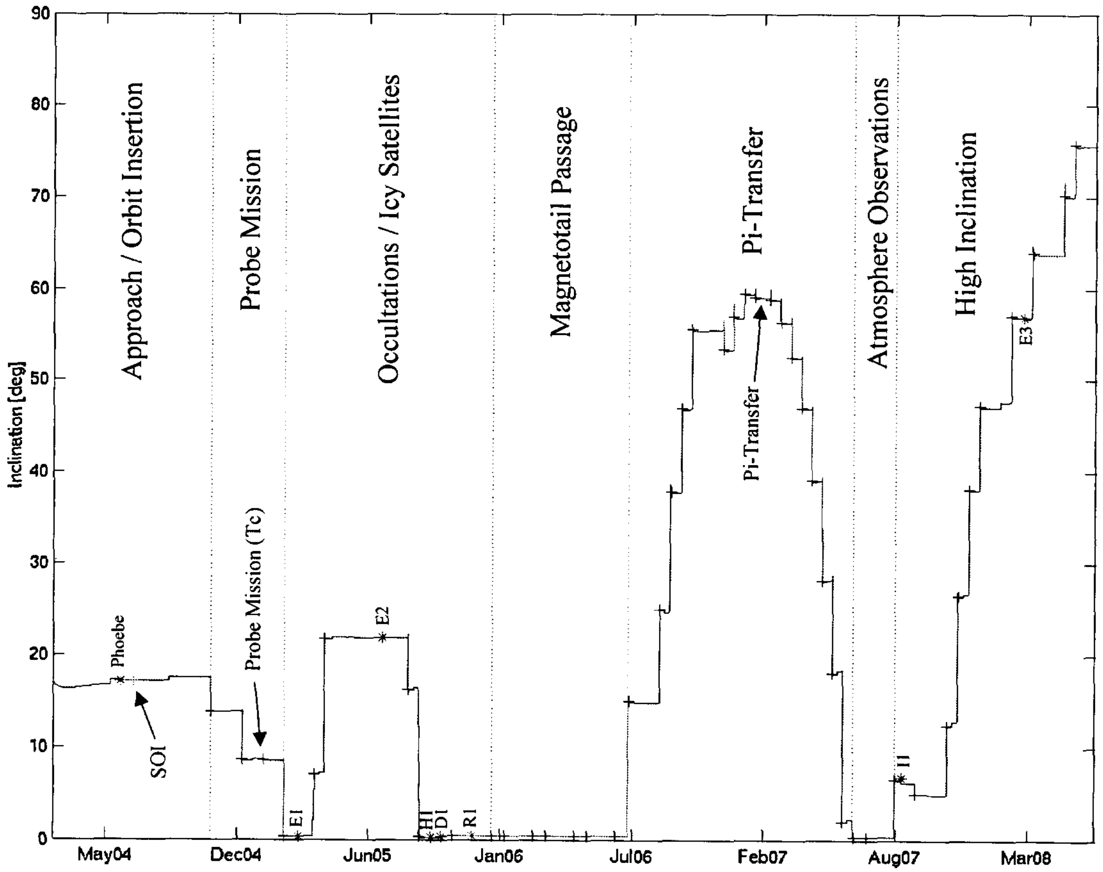


**Figure 1: Tour Phases**

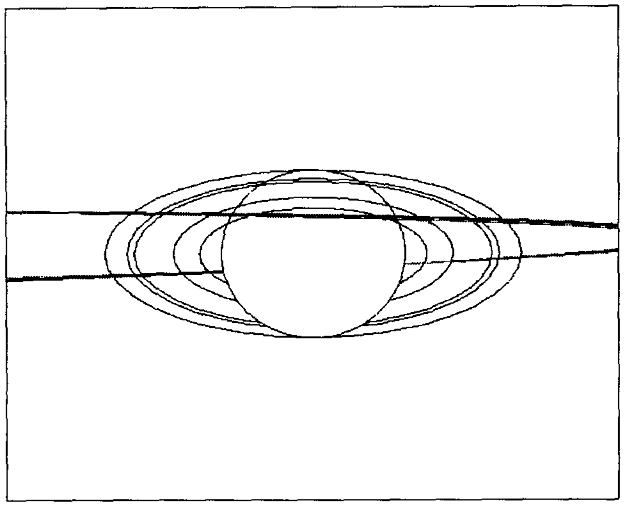

**Figure 2: Saturn-Earth Occultations from T5 to T6**

## PI-TRANSFER (T16-T33)

For the magnetotail observations, Cassini's apoapsis is behind Saturn as seen from the Sun. From this geometry, Cassini's apoapsis needs to be moved to the other side of Saturn for atmospheric observations. Then the apoapsis will be between Saturn and the Sun to allow observations of Saturn's entire disc in sunlight.

A Pi-Transfer is used to flip the Titan encounter 180° to the other side of Saturn more rapidly than could be done with non-resonant transfers. The Pi-Transfer occurs between T24 and T25, but requires many more flybys to set up the inclination needed for the transfer. The flybys from T16-T24 raise the inclination to the ~59° required for the Pi-Transfer. Then the flybys from T25 to T33 lower the inclination back into Titan's orbit plane so that non-resonant transfers can be used to set up the geometry required for the atmospheric observations. This phase has many low altitude Titan flybys, which are valuable for Titan science. Also, the T20-T21 transfer provides geometry favorable for ring observations.

## ATMOSPHERE OBSERVATIONS (T33-T35)

The non-resonant transfers in this phase of the mission provide geometry favorable for observations of Saturn's atmosphere. During this phase Cassini's apoapsis is between Saturn and the Sun. This allows Cassini to spend a long time above the daylight side of Saturn and provides the distance needed to observe Saturn's entire disc. At the end of this phase, the proper geometry is achieved to set up the near polar Saturn / ring occultations in the next segment.

## HIGH INCLINATION (T35-T44)

T35 begins a sequence that raises the inclination to ~75° with the periapsis below the illuminated side of the ring plane for close observation of the rings and Saturn's high latitudes. Like the Pi-Transfer sequence, this phase has many low altitude Titan flybys. The first targeted Iapetus encounter (I1) is on the T35-T36 transfer, and the third Enceladus encounter (E3) is on the T41-T42 transfer. The E3 encounter is unique in that it is eclipsed by Saturn during the closest approach.

The Cassini primary mission ends on July 1, 2008. The T44 flyby's aimpoint is targeted to set up a Titan flyby on July 31, 2008 for a possible extended mission.

## ORBIT DETERMINATION STRATEGY

Accurate delivery of the spacecraft to each satellite encounter requires an accurate knowledge and prediction of the location and velocity of the spacecraft relative to the satellite. The knowledge and prediction process has several components that must all work together to achieve the desired results.

The first component is the accurate determination of the orbits of the major Saturnian satellites. Prior to the approach of Cassini to Saturn, the knowledge of the satellite orbits is based on hundreds of years of ground based observations. While this data provides very accurate knowledge of the period of the orbits, the great distance from Earth to Saturn results in uncertainties of hundreds of kilometers in the exact location of the satellites. The reduction of the uncertainty to the few kilometer level necessary to successfully navigate Cassini will be accomplished using images of the satellites taken by the Cassini Narrow Angle Camera (NAC). The strategy is to begin an intensive imaging campaign about 4 months prior to SOI and continue updating the satellite ephemerides throughout the tour[9]. Full convergence is expected to extend about one year into the tour and then image frequency is reduced to a maintenance level. The frequency of optical navigation images is listed in Table 3. As a result of the repeated flybys, Titan's ephemeris will be determined, using the radiometric data, to a few kilometers in the same time period.

As noted earlier, the flybys of Titan provide the energy necessary to accomplish the orbit changes demanded by the selected tour. As the satellite ephemerides are improved the predicted location of the satellites at the times of the targeted encounters will change. The plan for collecting the science data requires that both the location and time of the targeted flybys be accurately predicted many weeks prior to the actual encounter. There are two techniques available to compensate between the predicted and actual location of the satellites. First the maneuvers can be targeted to achieve both the flyby location and the time of the encounter. For small changes in the ephemerides, on the order a few kilometers, the additional propellant costs are acceptable. However for large changes the reference trajectory must be adjusted to fit with the updated satellite ephemerides. Depending upon the changes in the location of the major satellites (primarily Titan), an update to the reference trajectory may be necessary once or twice prior to SOI and possibly three times after SOI.

**Table 3: OPTICAL DATA SCHEDULE DURING TOUR**

| Mission Phase | Image Rates | Comments |
|---|---|---|
| General | | Narrow angle Camera (NAC); Frames of all 9 major satellites. |
| SOI-Titan C | 3 frames/day | Initial Saturn orbit phase |
| Titan C – Titan 6 | 1.65 frames/day | Satellite ephemeris convergence |
| Titan 6 – End of Mission | 0.5 frames/day | Satellite ephemeris maintenance |

The second component of the orbit determination process is the determination of the location of the spacecraft in the Saturn system. The plan is to use a combination of both radiometric data (Doppler and ranging) and optical data from the NAC to accomplish this task. The frequency of radiometric tracking passes is listed in Table 4[10]. The same optical data noted above for the satellite ephemeris determination also provides information on the location of the spacecraft relative to the satellites.

The third component is the short term prediction of spacecraft and satellite orbits. Accurate prediction is accomplished using the validated models of the gravity fields and the non-gravitational forces acting on the spacecraft. Many of the parameters in these models are estimated as a part of the OD process. Due to the perturbations introduced by the Titan flybys, the short term predictions are generally limited to only a few days past the next Titan encounter. The current plan is to publish an updated local spacecraft trajectory as a part of each maneuver design. This update would include the predicted maneuvers and would extend a few days past the next Titan encounter. In a few cases additional deliveries are necessary.

**Table 4: RADIOMETRIC DATA SCHEDULE DURING TOUR**

| Mission Phase | Tracking Data Pass Rates | Comments |
|---|---|---|
| General | At least one pass per day. Doppler: at least 6 hours per day. Range: at least 3 hours per day. | X-band 2-way Doppler and range. At least 1 hour of tracking per day, on average, from a second DSN complex; at least four tracks from second DSN complex, evenly spaced, between targeted encounters. At least 2 hours of tracking for every scheduled tracking pass. |
| Start of S07 Sequence to Titan C | At least two passes per day. Doppler: at least 13 hours per day. Range: at least 6 hours per day. | X-band 2-way Doppler and range from northern hemisphere tracking stations. Requirement relaxed to one pass around middle of two day interval centered on Iapetus non-targeted flyby of 1 Jan 2005. |
| *Near-Titan Periods | At least one pass per day. Doppler: at least 6 hours per day. Range: at least 3 hours per day. | X-band 2-way Doppler and range. For the interval from pre-Titan maneuver to Titan-12h and the interval from Titan+12h to post-Titan maneuver. At least 2 hours of tracking for every scheduled tracking pass. |
| Tour Maneuvers | Before: at least 2 hours of tracking (Doppler and range) within 4 hours prior to maneuver. After: at least 2 hours of tracking (Doppler and range) within 4 hours after maneuver. | X-band 2-way Doppler and range. |

*A near-Titan period is defined as the period from pre-Titan maneuver to post-Titan maneuver.

## PROCESSING ASSUMPTIONS

In general, orbit determination shall be performed over data arcs spanning approximately 1.5 spacecraft revs around Saturn, with each arc beginning near Saturn apoapsis and ending near Saturn periapsis. In this manner, each arc has nearly 0.5 revs of overlap with the next arc. Longer arcs are prohibited by integration errors and nonlinearities. In many cases, targeted satellite flybys occur on consecutive revs. The first flyby within the segment allows the spacecraft ephemeris to be quickly correlated with the satellite ephemeris, thereby improving OD accuracies for the second flyby.

To advance the spacecraft initial epoch from one arc to the next, spacecraft, satellite, and planet ephemerides are estimated to convergence using tracking data up to the desired new initial epoch. The spacecraft ephemeris is then re-integrated (based on the converged solution) and interpolated to obtain the spacecraft state at the advanced epoch. The post-fit covariance from the converged solution is then used to define the satellite partition of the *a priori* covariance for solutions with the advanced epoch. In this manner, information content of tracking data obtained prior to the new initial epoch and relevant to the satellite ephemeris is retained.

In general, it will not be necessary to update the spacecraft and planet ephemeris covariance partitions when advancing the epoch of the spacecraft. Large *a priori* spacecraft ephemeris uncertainties converge quickly in the presence of Saturn's gravitational signature. Current planet ephemeris uncertainties in solar system barycentric space do not significantly impact Saturn-centered spacecraft uncertainties.

## FILTER CONFIGURATION

Table 5 and Table 6 contain *a priori* uncertainties and other filtering aspects to be implemented in the tour. The "unmodeled" ("considered") parameters roughly account for systematic errors in modeling. These are errors that cannot be improved by the filter, since the model is deficient. The consider treatment's principal benefit is to flag errors which could cause problems if ignored.

Stochastic non-gravitational accelerations are used to model a spacecraft fixed acceleration caused by thermal radiation from the radioisotope thermoelectric generators (RTG). While the direction of the acceleration depends on the spacecraft attitude, high fidelity modeling of the spacecraft attitude is not planned. Process noise is implemented to account for the mismodeling. Correlations between successive batches are assumed to be zero and an update interval of 12 hours roughly reflects the frequency of orientation changes for science observations.

During the Huygens probe delivery phase, the spacecraft will remain Earth-pointed to allow for continuous monitoring of the probe/spacecraft combination, to simplify operations, and to reduce OD uncertainties. The spacecraft attitude will be accurately modeled, negating the need for process noise. The non-gravitational acceleration is instead estimated as a constant parameter.

Cassini's attitude will generally be maintained via the Reaction Wheel Assembly (RWA) and angular momentum desaturations will be required. Because Cassini's Z-facing thrusters are uncoupled, desaturations will impart a $\Delta V$ along the spacecraft Z-axis. The navigation system will plan for trajectory perturbations caused by these events by including predicted $\Delta V$ models in the generation of the spacecraft ephemeris. After each event, which is commanded to occur over a tracking pass, the navigation system will reconstruct the $\Delta V$ based on Doppler data. Since the $\Delta V$ is directed along the spacecraft Z-axis and since the spacecraft -Z axis is directed towards Earth while tracking, the $\Delta V$ reconstruction accuracy is limited only by the accuracy of the Doppler data.

A large $\Delta V$ uncertainty is expected at many of the targeted satellite flybys, where the attitude control mode will transition from reaction wheels to RCS thrusters. Thrusters become necessary to accommodate high turn rates and to maintain adequate attitude control authority. Pre-tour analyses assumed a conservative uncertainty of 160 mm/s per axis but the actual uncertainty will vary depending on the amount of hydrazine consumed.

For optical navigation pictures, the camera pointing direction in inertial space is determined by the star images, because the stars' coordinates are well known. The measured location of the satellite image then provides the inertial direction from the spacecraft to the apparent position of the satellite when the picture was taken. Each picture becomes in effect a two-dimensional angular measurement---of the satellite's apparent right ascension and declination---provided that the reference star background is sufficient to determine the camera pointing. Two star images in a picture determine the camera pointing completely, with an accuracy that depends on the centerfinding errors of the star images. Additional star images provide incremental improvement to the knowledge of the pointing, since they decrease the pointing uncertainty. If there is only one star image, however, the camera can in principle rotate arbitrarily about the line of sight to the star, and therefore the data content is reduced: the angular separation between the star and the satellite is accurately known, but the "position angle" of the satellite with respect to the star is known only to the extent that the camera's twist orientation is known from other sources. The uncertainty ellipse in the satellite's apparent right ascension and declination will therefore be stretched into a cigar shape, with a long axis perpendicular to the line joining the spacecraft and the star. For this reason pictures with at least two usable stars are superior to one-star pictures.

**Table 5: FILTER PARAMETERS (EXCLUDING EPHEMERIS PARAMETERS)**

| Name | Modeled *A Priori* 1σ Error (Estimated) | Unmodeled *A Priori* 1σ Error (Considered) | Comments |
|---|---|---|---|
| *All Phases* | | | |
| Spacecraft epoch state | 150 km - ∞, 100 mm/s - ∞ | | Solutions are generally insensitive to epoch state error since they are strongly data driven. |
| Maneuvers | Variable | | Depends on nominal ΔV magnitude and propulsion system implemented. |
| Stochastic camera pointing | 1° per axis | | RA, Dec, twist angles. |
| Station locations | | 2-3 cm per axis | Reference 11 |
| Troposphere | | 1.0 cm | Zenith range delay. |
| Ionosphere | | 4.0 cm day 1.0 cm night | Range delays. |
| Earth orientation parameters | | 10 cm per axis | X, Y pole position, TAI-UT1. |
| Coherent Doppler data | 0.2 mm/s | | 60 second compression. |
| Ranging data | 75 m | | |
| Optical data | Titan = 1 pixel<br>Icy sats= 0.5 pixel<br>Stars = 0.25 pixel | | No optical data for SEP < 3° and within 12 hours of a satellite flyby. |
| Angular momentum desaturations | ~5 mm/s | | Along spacecraft Z-axis. |
| RCS science turns | 160 mm/s per axis | | Near satellite closest approaches. |
| *Tour* | | | |
| Stochastic non-gravitational acceleration | $4.5\times10^{-12}$ km/s$^2$ | | Per axis. 12h batches, white noise. |
| *Probe Delivery* | | | |
| Probe release | 1.3 mm/s per axis<br>12 mm/s per axis | | Orbiter uncertainty<br>Probe uncertainty |
| Detumble | 5 mm/s per axis | | AACS reconstruction capability |
| Constant non-gravitational acceleration | $2.1\times10^{-12}$, $6.7\times10^{-13}$, $7.6\times10^{-14}$ km/s$^2$ | | 50% of nominal acceleration caused by RTG radiation. |

The planet and satellite errors in Table 6, based on planet ephemeris DE410[12] and satellite ephemeris SAT136[13], will improve as additional ground based observations are collected and processed. Substantial improvements will be realized with the addition of optical navigation pictures and radiometric data acquired through satellite flybys.

## MANEUVER STRATEGY

The fundamental purpose of the navigation system is to direct the Cassini orbiter and the Huygens probe to follow the reference trajectory outlined previously. The reference trajectory defines a sequence of targeted Titan and icy satellite encounters that comprise the prime mission Saturn Tour. The maneuver strategy always targets the orbiter to achieve the encounter conditions specified in the reference trajectory. The targeted encounters represent a series of control points that only change as a result of modifications in the reference trajectory.

The corrections must be implemented in a way that is reliable and robust. For example, a maneuver design won't be uplinked to the spacecraft until the start of a tracking pass for maneuver execution, i.e., six hours before burn start, to maximize the time available to accomplish the OD process. Provision is also made for a backup response (backup TCM/OTM) in case any maneuver should fail or abort. For each maneuver a separate location is typically called out one day after the prime location.

**Table 6: FILTER EPHEMERIS PARAMETERS**

| Name | *A Priori* 1σ Error | | Comments |
|---|---|---|---|
| **Saturn and Satellites** | | | |
| | RSS Pos (km) | Mass ($km^3/s^2$) | Rounded RSS of position components. Saturn mass uncertainty is for system mass. Saturn position uncertainty is at SOI. Satellite position uncertainties at 2 Jan 2004. |
| Saturn | 434 | 58 | |
| Mimas | 1183 | 0.05 | |
| Enceladus | 465 | 1.3 | |
| Tethys | 348 | 0.05 | |
| Dione | 263 | 0.02 | |
| Rhea | 225 | 3.78 | |
| Titan | 182 | 0.88 | |
| Hyperion | 684 | 0.35 | |
| Iapetus | 416 | 15.08 | |
| Phoebe | 1618 | 0.23 | |
| **Other** | | | |
| Saturn gravity field | $6.0\times10^{-6}$, $2.7\times10^{-5}$, $2.8\times10^{-5}$ | | $J_2$, $J_4$, and $J_6$ (unnormalized) |
| Saturn pole | $3.6\times10^{-3}$, $1.8\times10^{-4}$ | | RA and Dec (degrees) |

## PROPULSION SYSTEMS

The Cassini spacecraft has two independent propulsion systems, each with its associated propellant tanks. The bi-propellant MEA (Main Engine Assembly) with a 445 Newton thrust is used for larger maneuvers, while the RCS (Reaction Control System, 2.4 Newtons maximum) thrusters are used for small corrections (Figure 3). A boundary in expected ΔV magnitude is applied to each maneuver to decide which engine to use. Table 7 shows the Gates execution error model[14] for the Main Engine and RCS, currently being used by the Navigation Team for statistical analysis. The main engine proportional model has been updated post-launch, based on maneuvers executed to date, which covered a wide range of magnitude—less than 10 m/s, several 10's of m/s, and over 100 m/s.

**Table 7: MANEUVER EXECUTION ERROR MODEL (1σ)**

| | | Main Engine | RCS |
|---|---|---|---|
| Magnitude | Proportional | 0.2% | 2.0% |
| | Fixed | 10 mm/s | 3.5 mm/s |
| Pointing (per axis) | Proportional | 3.5 mrad | 12 mrad |
| | Fixed | 17.5 mm/s | 3.5 mm/s |

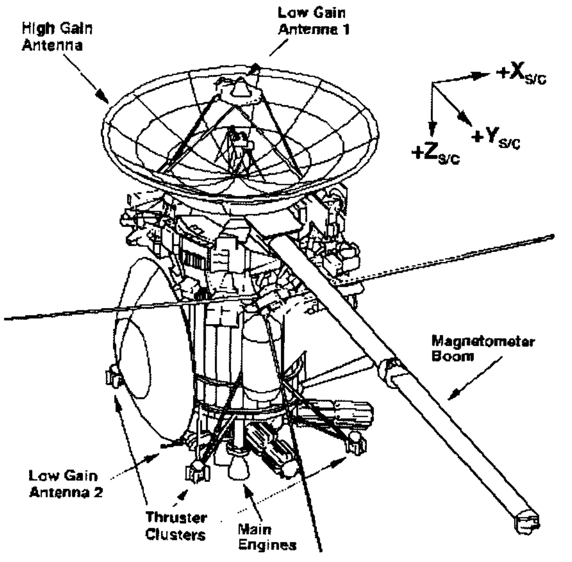


**Figure 3: Cassini Spacecraft**

The fixed error levels are larger for the main engine while proportional error levels are larger for the RCS. Thus, smaller maneuvers favor the use of RCS. Figure 4 shows the trade off in maneuver execution accuracy versus maneuver magnitude. Currently, the boundary is set at 0.5 m/s.

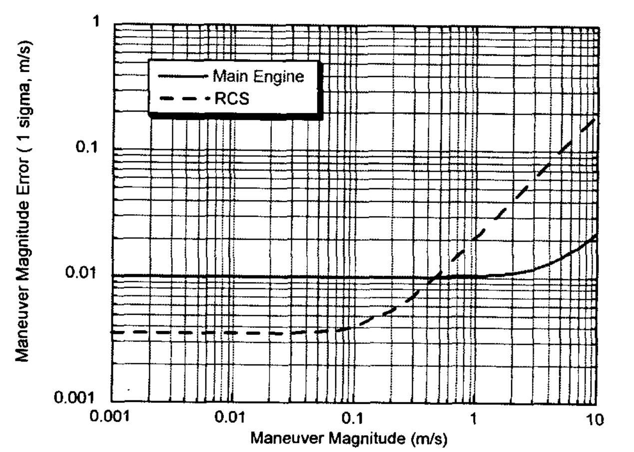


**Figure 4: Maneuver Execution Error vs. Magnitude**

## GENERAL PERSPECTIVE

Control of the trajectory to the targeted encounters is typically accomplished with three Orbit Trim Maneuvers between each targeted encounter. In general the OTMs are scheduled 3 days after the targeted encounter (the cleanup maneuver), near the apoapsis between the targeted encounters and 3 days prior to the next targeted encounter (Figure 5). There are numerous exceptions to this general sequence. The cleanup maneuver and the near apoapsis OTMs are coupled and provide control to the orbiter trajectory to the next encounter. In many cases this sequence includes a deterministic maneuver required to achieve the reference trajectory. The approach maneuver provides the delivery accuracy at the next encounter.

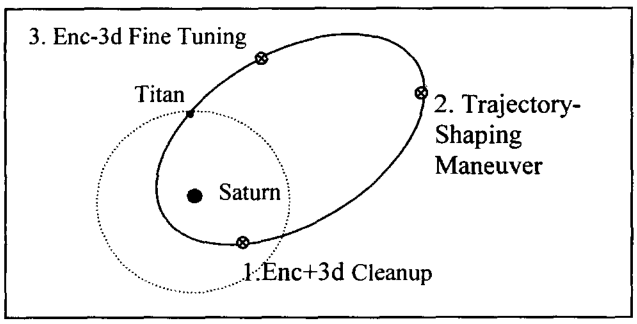


**Figure 5: Three OTMs per Encounter**

In order to place this strategy in some perspective, it should be noted that the flybys of Titan provide the major changes in the orbiter's trajectory necessary to accomplish the mission and the orbiter's propulsion system provides only the fine tuning. Figure 6 illustrates the equivalent ΔV provided by a Titan encounter as a function of the flyby altitude.

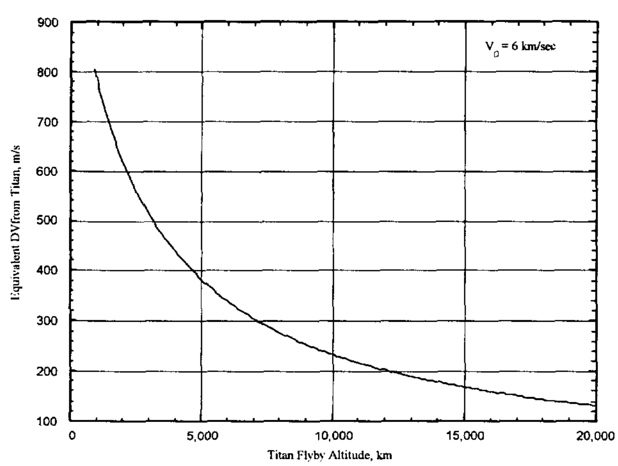


**Figure 6: Equivalent ΔV from a Titan Flyby**

Note that a Titan flyby at an altitude of 950 km imparts an equivalent ΔV of about 800 m/s to the spacecraft. Since the orbiter has a total ΔV capability after SOI and PRM of less than 500 m/s, missing almost any planned Titan flyby would have serious consequences. If this occurred, then a replanning of the remaining portion of the tour would be required.

Furthermore, because of the slope of the curve, changes in the planned altitude cause changes in the Titan ΔV. These errors in the Titan ΔV must be compensated for by maneuvers after the flyby. The slope of the curve at 950 km altitude is 0.21 m/s/km. Thus an error of 5 km in the Titan flyby altitude changes the Titan ΔV by about 1 m/s. Since the correction cannot be applied immediately, the correction cost is generally greater than the initial cost. Allowing the correction to be accomplished by multiple maneuvers and combined with deterministic maneuvers minimizes the spacecraft propellant cost.

## TARGETING STRATEGY

A two-maneuver optimization scheme will divide the cost in two parts such that their sum is minimized. However, a two-impulse solution minimizing the cost only in the 'current' leg usually introduces asymptote errors in the downstream legs, which become costly if left unchecked. One way of controlling these asymptote errors is to actively vary the upcoming flyby aimpoint based on the particular flyby errors incurred at the previous flyby, which requires frequent command sequence changes. This amounts to redefining the reference trajectory after each flyby. Due to the short time interval between flybys, active aimpoint variations would be operationally infeasible. Instead, the Cassini Navigation Team has adopted a chained two-impulse maneuver strategy[15,16] as described below, which couples the first and second maneuvers across several encounters but does not involve flyby aimpoint variations once a reference trajectory segment has been chosen. This scheme is illustrated in Figure 7, where a straight line is used as a generic representation of the spacecraft trajectory segment spanning encounters i through i+3, with each 'cross' marking an OTM.

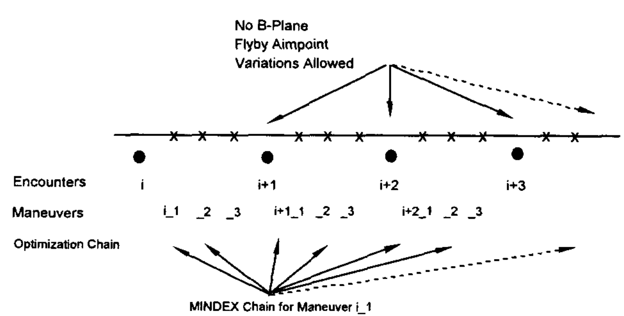

**Figure 7: Chained Two Impulse Maneuver Strategy**

Note that for N downstream encounters, 2*N maneuvers are being optimized (6*N parameters) and 3*N constraints are in effect (**B•R**, **B•T**, and TF). The third maneuver in each leg is not included since it is best left as a purely statistical final tuning. Hence, the first maneuver in each leg is computed by minimizing a cost function of the following form:

$$J_i = \underbrace{\underbrace{\left|\Delta v_{i\_1}\right| + \left\|\Delta v_{i\_2}\right|}_{leg\,i} + \underbrace{\left|\Delta v_{i+1\_1}\right\| + \left|\Delta v_{i+1\_2}\right\|}_{leg\,i+1} + \underbrace{\left|\Delta v_{i+2\_1}\right\| + \left|\Delta v_{i+2\_2}\right\|}_{leg\,i+2}}_{2\ maneuvers\ in\ each\ leg} + \cdots$$

$$= \sum_{m=0}^{n} \left\{\left|\Delta v_{i+m\_1}\right| + \left|\Delta v_{i+m\_2}\right|\right\}$$

subject to constraints

$$\Delta(\mathrm{B}\bullet\mathrm{R})_{i+1} = 0,\quad \Delta(B\bullet T)_{i+1} = 0,\quad \Delta TF_{i+1} = 0$$

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

The parameter 'n' representing the number of downstream encounters beyond the current one, was set at 4 in a linear perturbation analysis tool to compute statistical results. Hence each cost function consists of 10 maneuvers across five encounters, or 5 pairs of cleanup and near apoapsis maneuvers (the bulk of the benefit of optimization is achieved with n=2 or 3; hence, the actual operations might employ a strategy chaining 3 or 4 encounters). Note that this optimization strategy is to be used only for the cleanup maneuver after each flyby. The second and third maneuvers are targeted to the same reference flyby conditions, simplifying operations considerably when maneuvers are often spaced barely 4 days apart. Of course, the reference trajectory itself might be updated to redefine a set of flyby conditions, but this does not call for a more general re-optimization strategy with aimpoint variations based on each flyby error.

## CONCLUDING REMARKS

An orbit determination covariance analysis coupled with a maneuver Monte Carlo analysis was performed in order to predict the ΔV cost required to maintain the spacecraft on the reference trajectory. The strategy outlined in this paper allows the navigation system to meet its mission objective with 95% ΔV margins of 134 m/s (bi-propellant MEA) and 56 m/s (RCS).

From the post-interplanetary cruise to the pre-T3 flyby phase, the ΔV cost is heavily dominated by deterministic, i.e., trajectory 'shaping' maneuvers. This results in an average subtotal of approximately 1163 m/s before T3, with barely 5 m/s in standard deviation. Results for the Post-Huygens tour are shown in Figure 8 in the form of 'cumulative' ΔV cost[17]. The ordinate starts at the pre-T3 contribution to provide a predicted running total to end of mission of approximately 1600 m/s at the 95% level. The abscissa is the encounter number of the targeted flybys, T3 being the 4$^{th}$ and T44 the 52$^{nd}$.

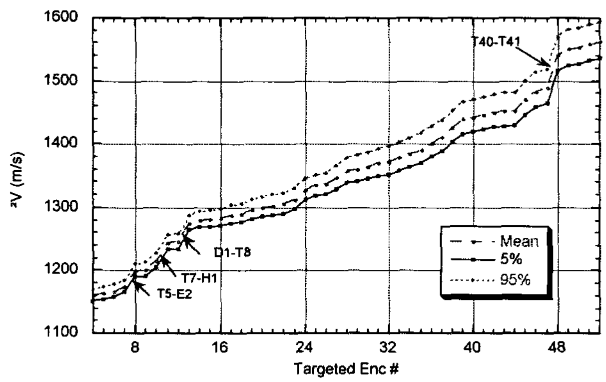


**Figure 8: Cumulative ΔV Cost for Post T3 Tour**

The deterministic ΔV cost for the Post-T3 tour is approximately 287 m/s, while the combined (deterministic + statistical) cost is approximately 400 m/s in the mean, and 430 m/s at the 95% level. Hence, the predicted ΔV estimate for the post-T3 tour is 'heavy' in statistical cost. The spread around the mean is narrow—the difference between the 5% low and 95% high is only about 60 m/s.

Since there are 48 flyby to flyby legs here, this comes to an 'average' of about 9 m/s per flyby at the 95% level. As readily observed in the plot, however, the cost is not spread evenly among encounters. The sharp rises in the early portion of the tour are due to the large deterministic maneuvers in T5-E2, T7-H1, D1-T8, and there is another large one in T40-T41 legs. That three out of these four legs involve transfers either to or from icy satellites underscores the expensive nature of 'squeezing' targeted icy satellite flybys between Titan-Titan encounter sequences.


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