Cassini Tour Redesign for the Huygens Mission

Nathan J. Strange,[1] Troy D. Goodson,[2] and Yungsun Hahn[3]

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099

The Cassini spacecraft will arrive at Saturn in 2004 carrying the Huygens probe which will descend into the atmosphere of Saturn's moon Titan. The beginning of the Cassini tour has been redesigned in order to work around the probe relay problem that was discovered during tests in February 2000. An extra 32-day orbit has been inserted at the beginning of the tour, and the orbiter altitude has been increased during the probe delivery flyby. This paper details the changes to the tour.

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. Cassini will be the first spacecraft to orbit Saturn and carries the Huygens probe which will be the first spacecraft to land on Saturn's moon Titan.

The Cassini-Huygens spacecraft will fly by Saturn's moon Phoebe on June 11, 2004 and insert into Saturnian orbit on July 1, with the first Titan encounter on October 26. The Huygens probe will be released on December 24, 2004 and will arrive at Titan on January 14, 2005.

During Cassini's four year tour of the Saturnian system[1] it will study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites. The Cassini orbiter and the Huygens probe will also study Titan's atmospheric structure and composition as well as Titan's surface topography.

In February 2000, a probe checkout test discovered that the bit synchronizer of the Huygens receiver onboard the Cassini orbiter has a bandwidth that is too small to accommodate the Doppler shift of the relay signal.[2] Shortly thereafter, an ESA independent enquiry board formed the joint ESA/NASA Huygen's Recovery Task Force (HRTF). Work by the HRTF has characterized the performance of the receiver[2,3] and developed a plan to recover the probe mission.[3,4,5] JPL's Cassini program office has made changes to the Cassini trajectory in support of the HRTF recovery plan.

In order to recover the probe mission, the Cassini tour at Saturn has been altered to reduce the Doppler shift between the orbiter and the Huygens probe. The altitude of the orbiter on the probe delivery encounter has been raised so that the radial component of the orbiter's velocity relative to the probe is reduced, and hence the Doppler shift of the relay signal is also reduced. Further improvement of the relay link may be possible by pre-heating the probe[3,6] prior to arrival at Saturn. At the time of this writing, the feasibility of the pre-heating option is under study.

The HRTF changes to the Cassini tour allow the recovery of the Huygens mission objectives while protecting the science of the Cassini tour. This is done by isolating major trajectory changes to a section of the tour previously dedicated to the probe mission[7,8] (i.e., before the T3 Titan encounter).

Trajectory Redesign

Reducing the Doppler shift of the signal from the Huygens probe to the Cassini orbiter is required to recover the probe mission. Trajectory changes can reduce the Doppler shift of the probe by either reducing the v-infinity of the orbiter on the probe delivery orbit or by increasing the altitude of the orbiter's flyby.

[1] Engineering Staff, 818.393.1165, nathan.strange@jpl.nasa.gov, FAX: 818.393.4215, Member AIAA
[2] Engineering Staff, 818.393.7887, troy.goodson@jpl.nasa.gov, FAX: 818.393.4215, Member AIAA
[3] Engineering Staff, 818.393.0617, yungsun.hahn@jpl.nasa.gov, FAX: 818.393.4215, Member AIAA

Reducing the v-infinity of the orbiter's flyby reduces the energy of the orbiter relative the probe and hence the velocity. Since Titan is the only body available for gravity assists at Saturn, it is not possible to significantly change the spacecraft's v-infinity with respect to Titan without a v-infinity leveraging maneuver.[9] Moreover, we would also need to increase Cassini's v-infinity after the probe delivery in order to achieve the high inclination orbits required to meet the mission's science objectives. Such changes to the orbiter's v-infinity would require larger maneuvers and/or a complete redesign of the Cassini tour. Studies early in the recovery process found that Cassini does not carry enough propellant for such changes to v-infinity.[3,10]

A distant flyby can also be used to reduce the Doppler shift of the probe relay signal. Raising a flyby's altitude reduces the radial component of the orbiter's velocity relative to Titan, as shown in Figure 1. Although the actual Doppler shift of the relay link needs to also account for the probe's velocity and position during its descent and landing among other factors,[3,5] the orbiter velocity relative to Titan gives a way to make first order assessments of the Doppler shift.

Previous tour designs[7,8] delivered the probe on a 1200 km altitude flyby shown in Figure 1. This probe mission began 4 hours before periapsis and lasted approximately 3 hours. In this mission the radial velocity of the orbiter relative to Titan stayed between 5.6 and 5.5 km/s. Figure 1 shows that a 60,000 km altitude flyby starts at 4.6 km/s 4 hours before periapsis and decreases much more rapidly than the 1200 km flyby.

Figure 2 compares the altitude of the orbiter from Titan for both a 1200 km and a 60,000 km flyby. We see that at 4 hours before periapsis, a 1200 km flyby has an altitude of approximately 80,000 km and a 60,000 km flyby has an altitude of almost 100,000 km. However, at 2.6 hours before periapsis a 60,000 km flyby drops below 80,000 km for approximately 5 hours. Therefore, a probe mission on a distant flyby can be within the maximum range of the original probe mission if the mission starts closer to periapsis. Figure 1 shows that starting the probe mission later also results in less Doppler shift of the relay signal. It is possible to start the probe mission later if the geometry of the flyby allows, i.e. if the orbiter is high enough above the probe's horizon to maintain link for the whole 3 hour probe mission.

Delivering the probe on a distant flyby requires the insertion of an additional orbit into the tour. This is because a distant flyby does not produce sufficient bending to change Cassini's orbit period and still reencounter Titan. Therefore, an additional orbit equal

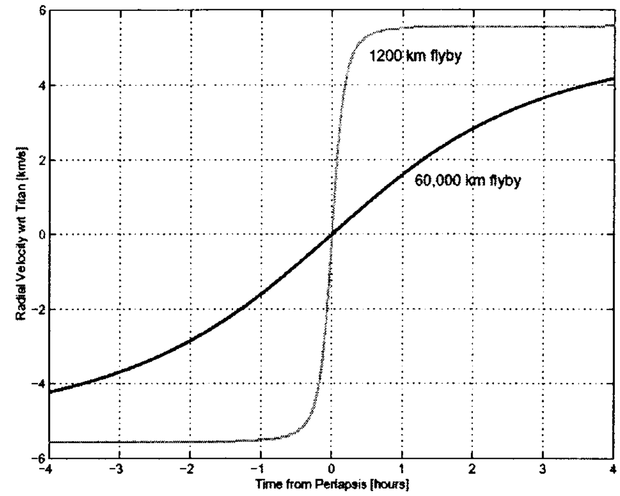

Figure 1: Flyby Range Rate

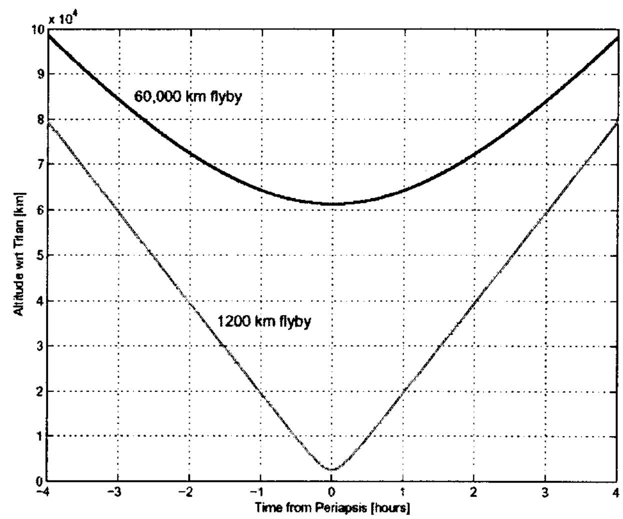

Figure 2: Flyby Range

in period to the orbit before a distant flyby must be added to the tour. An additional orbit can easily be inserted into the tour without modifying the sequence of Titan flybys after the insertion of the additional orbit. However, time sensitive events such as icy satellite flybys will be lost after the insertion of an extra orbit without redesign of the rest of the tour.

The HRTF conducted studies of inserting a distant flyby for probe delivery at the beginning,[11] middle,[12] and end[13] of the tour and found that changes to the beginning of the tour have the smallest impact on tour science. By moving the first Titan encounter earlier, a distant flyby can be inserted without disturbing the rest of the tour, as illustrated in Figure 3. The new tour, T2002-01, arrives at the first flyby 32 days earlier than the T18-5 tour and allows time to insert an extra 32 day orbit after the distant flyby and still return to the T18-5 tour on the T3 flyby. In this scenario, three new Titan

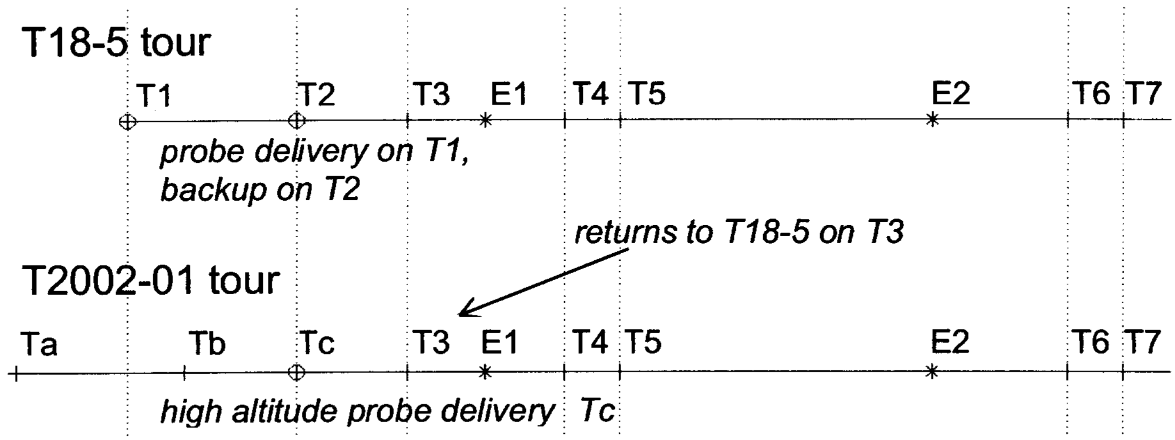

Figure 3: Timeline Comparison

flybys replace the first two Titan flybys of T18-5. In order to avoid the confusion of renumbering all of the flybys in the rest of the tour, the first three flybys of the new tour are renamed to Ta, Tb, and Tc.

The probe is now delivered on the Tc flyby in tour T2002-01 (see Figure 3). If the probe cannot be delivered on Tc due to some anomaly, there is an additional contingency delivery available.[3,4] This contingency would retarget Tc to a low altitude flyby and deliver the probe on a new high altitude flyby, Td. After Td, two new flybys Te and Tf replace flybys T3, T4, and T5 returning the contingency to the original tour at T6. Unfortunately, much important tour science before T6 is lost. The contingency looses two of the three targeted Enceladus flybys and three of seven diametric Saturn radio science occultations. Because of this severe impact on science, the contingency will be avoided except in the most extreme of cases.

The Distant Flyby

Although a distant flyby does not provide enough bending to allow a change of Cassini's orbit period, it does provide a small ΔV. This ΔV can be used to change Cassini's orbit inclination with an inclined flyby (i.e. a high B-plane[14] angle). However, a 60,000 km altitude flyby of Titan is equivalent to about 3 degrees of true anomaly in Titan's orbit. This means that an inclined distant flyby would require plane change maneuvers before and after the flyby. It is a much more effective use of propellant to perform an equatorial flyby and cancel out the small ΔV from the flyby with maneuvers than to perform the plane change maneuvers required for an inclined flyby.

Figure 4 is a schematic illustrating the two options for a distant equatorial flyby. A posigrade flyby (0° B-plane) decrease the post flyby orbit period and a retrograde flyby (180° B-plane) increases the post flyby orbit period. Two roughly 20 m/s maneuvers after the flyby are used to correct the post flyby period back to 32 days so that Cassini can reencounter Titan.

The probe is delivered by targeting both the orbiter and the probe to the probe entry conditions and then releasing the probe. After probe release an Orbiter Deflection Maneuver (ODM) is performed to retarget the orbiter to the proper flyby conditions. Not only does the ODM raise the orbiter's periapsis altitude, but it also delays the arrival of the orbiter at Titan. The time from the probe's arrival at the interface altitude (1270 km) and the orbiter's closest approach to Titan is called the Orbiter Delay Time (ODT).

The ODM for a retrograde distant flyby is much smaller than for a prograde distant flyby. This is due to an interaction between raising the orbiter's flyby altitude and increasing the delay time as shown in Figure 4.

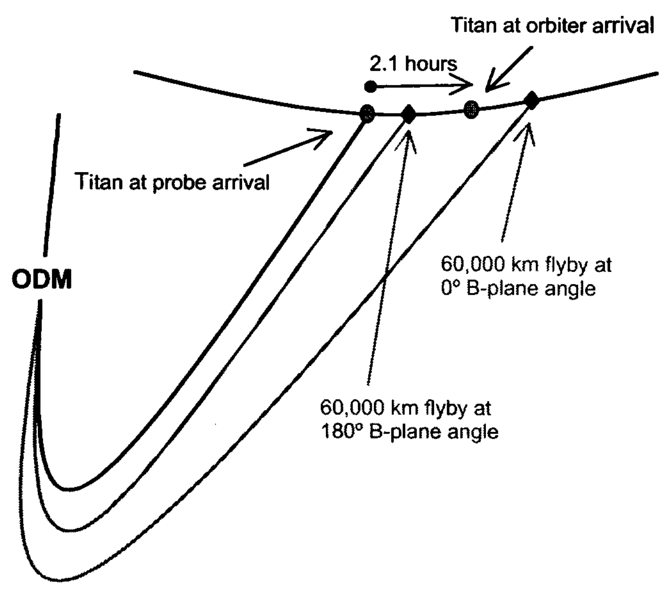

Figure 4: Probe Delivery Schematic

Titan travels approximately 20,000 km an hour. The ODM for a posigrade 60,000 km flyby with a 2.1 hour ODT must deflect the pre-flyby orbit by over 120,000 km. However, a retrograde flyby with the same parameters would only require a deflection of about 20,000 km from the ODM. This is because Titan's motion is in the opposite direction of the altitude change for a retrograde flyby (see figure 4). For a posigrade flyby the ODM is over 100 m/s, but for a retrograde flyby to ODM drops to around 20-30 m/s.

Another advantage of the retrograde flyby is that the orbiter is above the horizon of the landing after periapsis. In T18-5's prograde probe delivery flyby, the orbiter passed below the horizon of the landing site at periapsis. In T2002-01's retrograde flyby, the orbiter is above the horizon for 1-4 hours after periapsis[15,16] (depending on the landing site). A retrograde flyby allows a shorter ODT (i.e., a probe mission start closer to periapsis) which in turn improves both the orbiter probe range and reduces the Doppler shift (see Figures 1 and 2).

In tour T2002-01, the probe is delivered on a distant, 60,000 km retrograde flyby with an ODT of 2.1 hours. Extensive work at ESA has determined that this ODT and orbiter flyby altitude give the optimal link performance.[3,5] Table 1 shows the probe entry conditions and the Tc orbiter flyby conditions in tour T2002-01.

Table 1: Probe Delivery

Probe Interface Conditions	
Date:	14-JAN-2005
Time (Interface Alt.):	8:58 (UTC)
B-Plane:	170 deg
Flight Path Angle:	-64 deg
V-Infinity:	5.63 km/s
Interface Altitude:	1270 km
Tc Orbiter flyby	
Time (Periapsis):	11:04 (UTC)
Orbiter Delay Time:	2.1 hr
B-Plane:	180 deg
Periapsis Radius:	60,000 km
V-Infinity:	5.30 km/s

T2002-01 Flybys

The previously-baselined tour,[7,8] T18-5, has largely been maintained with changes limited to the beginning of the new tour (T2002-01). The first two flybys of the T18-5 tour (T1 and T2) have been replaced with three new flybys (Ta, Tb, and Tc). The probe delivery was originally on the 1200 km altitude T1 flyby and has now been moved to a distant flyby (60,000 km) on Tc.

Table 2 shows the targeted flybys in tour T2002-01.

Table 4: Non-Targeted Icy Satellite Flybys

Satellite	Date	Altitude [km]
Mimas	2004 JUL 01	77463.380
Dione	2004 DEC 15	83610.500
Iapetus	2005 JAN 01	63639.719
Enceladus	2005 FEB 17	2904.359
Tethys	2005 MAR 09	80347.069
Enceladus	2005 MAR 29	51233.316
Mimas	2005 APR 15	89793.667
Tethys	2005 MAY 02	92697.325
Enceladus	2005 MAY 21	78771.546
Mimas	2005 AUG 02	50885.881
Tethys	2005 SEP 24	28259.143
Enceladus	2005 OCT 12	35412.331
Rhea	2006 MAR 21	79911.354
Enceladus	2006 SEP 09	43160.509
Dione	2006 NOV 21	73245.523
Dione	2007 APR 24	98668.355
Tethys	2007 MAY 26	96706.287
Tethys	2007 JUN 27	15768.159
Mimas	2007 JUN 27	96239.336
Enceladus	2007 JUN 28	90430.951
Tethys	2007 AUG 29	51143.628
Rhea	2007 AUG 30	6437.571
Dione	2007 SEP 30	55049.147
Enceladus	2007 SEP 30	90779.192
Rhea	2007 NOV 16	81354.000
Mimas	2007 DEC 03	79531.486
Mimas	2008 APR 11	95962.536

Table 3: Beginning of T18-5 (The Previously-Baselined Cassini Tour)[a]

Encounter	Satellite	Time (UTC)	Altitude [km]	B-Plane [deg]	V-Infinity [km/s]
Ph	Phoebe	11-Jun-04 20:25	1000	0	6.36
T1	Titan	27-Nov-04 14:14	1200	-24	5.54
T2	Titan	14-Jan-05 10:16	1200	-61	5.53
T3	Titan	15-Feb-05 07:34	950	-40	5.54

[a]TOF = time of flight from SOI. B-plane = B-plane[14] angle relative to Titan pole. Period = spacecraft period after encounter. Revs = spacecraft revolutions after encounter. Inc. = inclination after encounter. Rasc = radius at ascending node. Rdes = radius at descending node. RS = units of Saturn radii. 1 RS = 60330 km (0.1 bar, equatorial radius).

Table 2: Tour T2002-01 (The New Cassini Tour)[a]

Encounter	Satellite	Time (UTC)	Altitude [km]	B-Plane [deg]	V-Infinity [km/s]
Ph	Phoebe	11-Jun-04 19:33	2000	0	6.35
Ta	Titan	26-Oct-04 15:30	1200	-39	5.66
Tb	Titan	13-Dec-04 11:37	2358	-49	5.66
Tc	Titan	14-Jan-05 11:04	60000	-180	5.38
T3	Titan	15-Feb-05 06:54	950	-43	5.58
E1	Enceladus	09-Mar-05 09:06	500	150	6.61
T4	Titan	31-Mar-05 19:55	2524	-149	5.61
T5	Titan	16-Apr-05 19:02	950	-77	5.63
E2	Enceladus	14-Jul-05 19:57	1000	-160	8.12
T6	Titan	22-Aug-05 08:40	4014	122	5.61
T7	Titan	07-Sep-05 07:50	950	68	5.63
H1	Hyperion	26-Sep-05 01:41	1000	180	5.62
D1	Dione	11-Oct-05 17:57	500	120	9.03
T8	Titan	28-Oct-05 03:58	1446	181	5.52
R1	Rhea	26-Nov-05 22:35	500	11	7.29
T9	Titan	26-Dec-05 18:55	10405	180	5.49
T10	Titan	15-Jan-06 11:36	2041	-180	5.48
T11	Titan	27-Feb-06 08:20	1812	180	5.51
T12	Titan	19-Mar-06 00:00	1949	-180	5.47
T13	Titan	30-Apr-06 20:53	1853	-180	5.49
T14	Titan	20-May-06 12:13	1879	-180	5.48
T15	Titan	02-Jul-06 09:12	1911	-181	5.48
T16	Titan	22-Jul-06 00:25	950	-91	5.52
T17	Titan	07-Sep-06 20:12	950	-24	5.54
T18	Titan	23-Sep-06 18:52	950	-80	5.54
T19	Titan	09-Oct-06 17:23	950	-74	5.54
T20	Titan	25-Oct-06 15:51	950	-11	5.55
T21	Titan	12-Dec-06 11:35	950	-121	5.53
T22	Titan	28-Dec-06 10:00	1500	-60	5.54
T23	Titan	13-Jan-07 08:34	950	-52	5.54
T24	Titan	29-Jan-07 07:12	2714	-68	5.54
T25	Titan	22-Feb-07 03:09	950	-55	5.83
T26	Titan	10-Mar-07 01:45	950	-48	5.83
T27	Titan	26-Mar-07 00:20	950	-58	5.83
T28	Titan	10-Apr-07 22:56	950	-66	5.83
T29	Titan	26-Apr-07 21:32	950	-73	5.83
T30	Titan	12-May-07 20:08	950	-79	5.83
T31	Titan	28-May-07 18:51	2425	-83	5.83
T32	Titan	13-Jun-07 17:46	950	-87	5.83
T33	Titan	29-Jun-07 17:02	1942	-8	5.85
T34	Titan	19-Jul-07 00:40	1302	181	5.86
T35	Titan	31-Aug-07 06:34	3217	-116	5.84
I1	Iapetus	10-Sep-07 12:33	1000	161	2.36
T36	Titan	02-Oct-07 04:48	950	120	5.90
T37	Titan	19-Nov-07 00:52	950	157	5.90
T38	Titan	05-Dec-07 00:06	1300	96	5.92
T39	Titan	20-Dec-07 22:55	950	101	5.92
T40	Titan	05-Jan-08 21:27	950	166	5.91
T41	Titan	22-Feb-08 17:39	950	140	5.95
E3	Enceladus	12-Mar-08 19:05	1000	0	14.59
T42	Titan	25-Mar-08 14:35	950	147	5.96
T43	Titan	12-May-08 10:09	950	-163	5.95
T44	Titan	28-May-08 08:33	1316	-168	5.95

[a]TOF = time of flight from SOI. B-plane = B-plane[14] angle relative to Titan pole. Period = spacecraft period after encounter. Revs = spacecraft revolutions after encounter. Inc. = inclination after encounter. Rasc = radius at ascending node. Rdes = radius at descending node. RS = units of Saturn radii. 1 RS = 60330 km (0.1 bar, equatorial radius).

After T3, T2001-01 has only a few small tweaks from tour T18-5. However, before T3 the tour modifications are more significant. For comparison, the beginning of T18-5 is shown in Table 3.

Table 4 shows the non-targeted icy satellite flybys in tour T2002-01. (Saturn's Icy Satellites are: Mimas, Enceledus, Tethys, Dione, Rhea, Hyperion, Iapetus, and Phoebe.) The changes to the tour have resulted in new, close non-targeted flybys of Iapetus (on Jan 1, 2005) and of Enceladus (on February 17, 2005). The Iapetus flyby is particularly exciting as it is of the opposite hemisphere from the targeted flyby (I1).

Maneuver Design

Given the trajectory design and its associated maneuvers, the remaining part of the maneuver design task is to place maneuvers for trajectory correction, i.e. flight-path control, and devise targeting strategies for the in-flight computation of all the ΔV maneuvers.

This task requires some model of the estimation, i.e. orbit determination, errors and ΔV execution errors that will be incurred in flight. Any contribution due to these errors is referred to here as the statistical part, alluding to the statistical nature of the models. Any non-statistical contribution is the deterministic part, where all estimation and execution is perfect.

The trajectory design described in Table 2 uses maneuvers that only have deterministic parts. The discussion below includes the both the deterministic and statistical parts of these maneuvers. Many of these maneuvers are clean-up (CU) maneuvers, such as PTM CU, which follows the Probe Targeting Maneuver (PTM). In reporting results, the deterministic and the 95th percentile level for ΔV magnitude are given. Statistics on the mission margin, viz. the ΔV available after accounting for the nominal completion of the prime mission, are also computed.

In the previously-baselined T18-5 tour there was an estimated 210 m/s ΔV margin (at the 95% level). The changes to the tour use 95 m/s of this margin, almost half of the ΔV available. Of the extra ΔV spent, 75 m/s is spent on a larger Saturn Orbit Insertion (SOI) maneuver and Periapsis Raise Maneuver (PRM) (also sometimes Pericrone-Raise (PCR) maneuver) in order to move the first Titan encounter 32 days earlier.

A maneuver analysis for tour 92-01, a tour whose initial orbits are similar to T18-5, has been presented previously.[17] The following discussion will provide an overview of results for T2002-01 with some comparison to T18-5. More detailed results will be presented in a later paper.

The First Rev

Figure 5 depicts the first three revolutions of the T2002-01 trajectory and its maneuvers, projected into Titan's orbital plane. The approach trajectory is punctuated by an encounter with Phoebe, but the critical event is the orbit insertion maneuver. The SOI maneuver's goal is to remove enough kinetic energy from the spacecraft so that Saturn's gravity captures it. SOI works in concert with PRM,[18] which targets the spacecraft to the first Titan flyby. These two maneuvers are among the mission's largest. In T18-5, SOI is about 620 m/s and PRM is over 330 m/s; in T2002-01, SOI is over 630 m/s and PRM is over 390 m/s.

If SOI is not executed or is incomplete, the spacecraft may not be captured by Saturn, making SOI a mission-critical maneuver. To help ensure that SOI is executed, the spacecraft has a back-up main engine assembly. Use of the back-up engine is controlled by fault-protection algorithms during SOI.[19] If flight software commands a main-engine swap, there will be a delay in the burn.

Timing is critical for SOI because it is an energy-altering maneuver. Changes in energy, to first order, vary as $\Delta E = \mathbf{V} \cdot \Delta \mathbf{V}$. As such, the effectiveness of the maneuver is greatest near pericrone where the spacecraft's speed is the greatest; effectiveness is also improved if the change in velocity is parallel to the velocity.

In order to mitigate the cost of delays in SOI, the pointing of the main engine nozzle will follow a vector that rotates at a constant rate, 0.008 degrees/second for T18-5 and T2002-01. This slewing is another unique aspect of SOI.

For recovery of the probe mission, SOI increases in size, but the rotation rate is not impacted. Although the turn rate is important for delays in the burn, it does not have much influence on the size of SOI. A change of 0.001 degrees/second gives a change of about 1 m/s in the size SOI.

Trajectory characteristics that are important to SOI and the first rev are listed in Table 5. Note that approach has remained largely unchanged; the miss distance has decreased by about 0.4%. The most influential change is in orbit period; this change shows up in the first pericrone passage that is 32 days earlier. Note that PRM also makes an adjustment, but it is very slight as changes to period are much more efficient at SOI.

A secondary influence is the change in SOI's starting time of about 9 minutes. This starting time puts more of the finite burn near pericrone in T2002-01 than in T18-5, increasing efficiency and reducing the size somewhat.

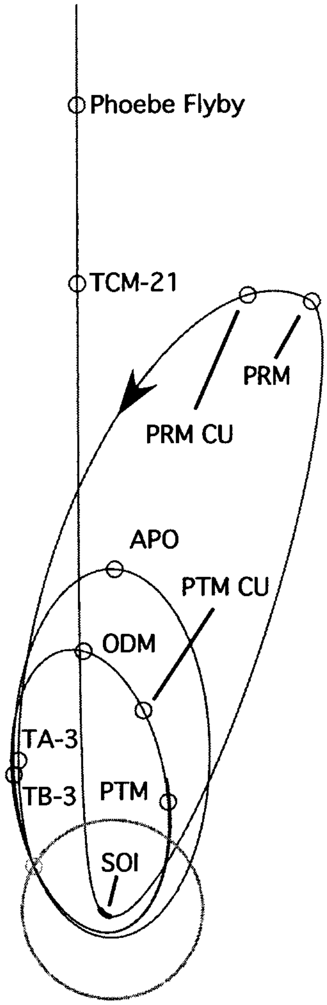

Figure 5: First Three Revs of T2002-01. First Three Revs of T2002-01. Diagram is projected into Titan's orbital plane. Labels denote maneuver locations. "CU" denotes clean-up maneuvers; "TA-3", "TB-3" denote maneuvers 3 days before Titan-A and Titan-B, respectively. "TCM-21" is the 21st cruise Trajectory Correction Maneuver.

Table 5: Selected Aspects of the First Rev of T18-5 and T2002-01. B is the B-plane[14] miss distance, θ is the B-plane angle, times are HH:MM:SS UTC, and TCA is time of closest approach.

	T18-5	T2002-01
Approach V_∞	5.204 km/s	5.204 km/s
Approach B	485,116 km	483,155 km
Approach θ	-24.36 degrees	-24.48 degrees
Arrival	1-Jul-2004	1-Jul-2004
SOI start time	01:03:00	01:12:00
Pericrone	02:38:51	02:38:55
SOI end time	02:38:50	02:47:01
PRM date	25-SEP-2004	23-AUG-2004
Apocrone	13-SEP-2004	27-AUG-2004
Pericrone	29-NOV-2004	28-OCT-2004
V_∞ to 1st Titan	5.538 km/s	5.655 km/s
B to 1st Titan	4,056 km	4,046 km
1st Titan TCA	27-NOV-2004	26-OCT-2004

Maneuvers for the Probe Mission

In both mission designs, the Probe-Targeting Maneuver (PTM) puts the probe (and orbiter) on an impacting trajectory. PTM is followed by release of the probe (separation) and then by the Orbiter Deflection Maneuver (ODM). The ODM targets the orbiter away from Titan and onto a trajectory favorable for the relay of data from the probe and resumption of the tour.

The changes in SOI and PRM facilitate the shift of this probe mission from T1 in T18-5 to Tc in T2002-01; the maneuvers for these missions are listed in Tables 6 and 7, respectively. In these tables, Deteterministic ΔV is only for the trajectory design, while 95% ΔV represents the ΔV required by 95% of cases in which random orbit determination and maneuver execution errors are accounted for.

The period of the probe-delivery orbit was about 150 days in T18-5, but is 32 days in T2002-01. This orbit period is quite influential on the maneuvers for the probe mission.[20] The size of PTM is a good indicator as in T2002-01 it is ten times it's size in T18-5. This larger size necessitates the use of a clean-up maneuver (PTM CU). ODM would also see a significant increase but the orbiter flyby was direct in T18-5 and is retrograde in T2002-1.

Table 6: Maneuver Data for T18-5. "Det. ΔV" denotes deterministic ΔV. "T1-63" is 63 days before Titan-1. Clean-up maneuvers are denoted CU.

MVR		Date	Det. ΔV	95% ΔV
SOI	T1-149	1-Jul-2004	618 m/s	620 m/s
PRM	T1-63	25-Sep-2004	334 m/s	335 m/s
PRM CU	T1-51	7-Oct-2004	0 m/s	3.85 m/s
PTM	T1-23	4-Nov-2004	1.21 m/s	1.42 m/s
Separation	T1-21	6-Nov-2004	27.5 mm/s	151 mm/s
ODM	T1-19	8-Nov-2004	48.9 m/s	49.3 m/s
ODM CU	T1-9	18-Nov-2004	0 m/s	1.07 m/s

Table 7: Maneuver Data for T2002-01. "Det. ΔV" denotes deterministic ΔV. "TC-23" is 23 days before Titan-C. Clean-up maneuvers are denoted CU.

MVR		Date	Det. ΔV	95% ΔV
SOI	TA-117	1-Jul-2004	632 m/s	636 m/s
PRM	TA-64	23-Aug-2004	392 m/s	393 m/s
PRM CU	TA-49	7-Sep-2004	0 m/s	4.62 m/s
PTM	TC-27	18-Dec-2004	12.1 m/s	12.5 m/s
PTM CU	TC-23	22-Dec-2004	0 m/s	180 mm/s
Separation	TC-21	24-Dec-2004	27.5 mm/s	151 mm/s
ODM	TC-16	29-Dec-2004	26.2 m/s	26.4 m/s

Tour Maneuver Strategy

During the primary mission, Titan flybys may be as little as 16 days apart, the rapidity of which presents a significant challenge for navigation. A trade-off must be made between maneuver placement for fuel use and for operational simplicity. For fuel use alone, one might desire at least three maneuvers: a mostly-statistical clean-up as soon as possible after an encounter, a mostly-deterministic trajectory-shaping maneuver (probably near apoapsis), and a final-targeting maneuver for the next encounter once the orbit determination uncertainties are sufficiently small. Operational simplicity demands as few maneuvers as possible and the greatest amount of time between them as can be accommodated.

The Cassini program has developed software to automate maneuver design and command sequencing such that the whole maneuver design process can be completed in two days. Allowing the orbit determination process one day after an encounter to collect data results in a placement for the clean-up maneuver at three days after the encounter.

The trajectory-shaping maneuvers are nominally placed near apoapsis and the final-targeting maneuvers are nominally placed at three days prior to the encounter. Maneuver placement may be seen in Figure 6.

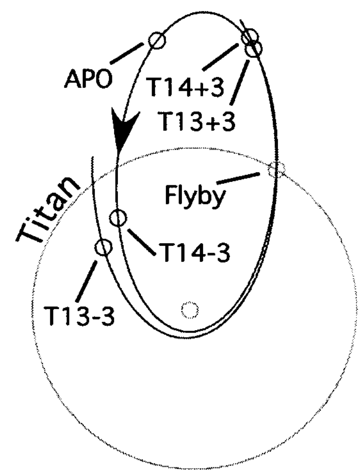

Figure 6. Typical maneuver placement for a leg of the primary tour mission. "T14-3" denotes a maneuver 3 days before the 14th Titan encounter (Titan-14). "APO" denotes a maneuver near apocrone.

The **ΔV** cost of the tour is held down by a two-impulse maneuver strategy between encounters. The clean-up maneuver is designed such that the sum of its cost and the *predicted* cost of maneuvers for the next four (or more) encounter legs is minimized. This minimization is constrained such that the trajectory-shaping and final-targeting maneuvers both achieve the *nominal* swingby aimpoint. In this way, there is usually no need for a deterministic component to the final-targeting maneuver, leaving room for the opportunity to cancel some of these final-targeting maneuvers in flight.

This strategy saves about 50 m/s at the 95% level for the whole primary tour mission. The maneuvers for the primary tour are listed in Table 8. The "name" column names maneuvers in a manner similar to the above discussion, "t03-3" is a maneuver three days before the third encounter with Titan, "t21+3" is a maneuver three days after the twenty-first encounter with Titan. Maneuvers labeled "~APO" in Table 8 are the trajectory-shaping maneuvers near apocrones.

The data listed in Table 8 is the result of a maneuver analysis whose details are beyond the scope of this paper. The analysis will be described in more detail in a later paper. This data is included in this paper to demonstrate typical maneuver sizes for this tour design.

A similar maneuver analysis had been performed for T18-5 and showed a **ΔV** margin of 215 m/s,[4] representing fuel available for handling further

Table 8: Summary of Maneuver statistics for Cassini's Primary Tour Mission. "t" is for Titan, "d" for Dione, "e" for Enceladus, "h" for Hyperion, "r" for Rhea, and "i" is for Iapetus. ΔV is in m/s.

Name	Mean	ΔV95	Name	Mean	ΔV95	Name	Mean	ΔV95
t03-3	0.78	1.81	t14+3	1.18	3.08	~APO	5.59	8.06
t03+2	0.49	1.19	~APO	1.28	2.77	t31-3	0.14	0.33
~APO	5.03	10.48	t15-3	0.44	0.99	t31+3	2.17	5.43
e01-3	0.11	0.22	t15+3	2.93	6.14	~APO	12.77	13.60
e01+3	0.88	2.23	~APO	0.17	0.38	t32-3	0.23	0.52
~APO	3.05	5.17	t16-3	0.12	0.24	t32+3	3.63	9.14
t04-3	0.12	0.28	t16+3	0.97	2.52	~APO	9.04	10.03
t04+3	1.44	3.63	~APO	5.72	6.29	t33-3	0.17	0.39
~APO	6.07	7.70	t17-3	0.37	0.90	t33+3	3.02	6.59
t05-3	0.14	0.29	t17+3	1.03	4.50	~APO	0.67	1.44
t05+3	2.92	8.51	~APO	13.44	14.72	t34-3	0.12	0.24
~APO	21.33	23.10	t18-3	0.28	0.61	t34+3	2.18	6.10
e02-6	1.39	3.42	t18+3	1.16	3.42	~APO	1.50	3.20
e02+p	0.70	1.83	~APO	5.43	6.61	t35-3	0.34	0.82
~APO	1.23	4.17	t19-3	0.13	0.28	t35+2	3.76	5.19
t06-3	0.10	0.21	t19+3	1.29	3.33	~APO	0.32	0.79
t06+3	1.44	4.15	~APO	0.64	1.47	i01-2	0.18	0.34
~APO	12.82	13.39	t20-3	0.10	0.19	i01+3	0.78	1.64
t07-3	0.16	0.36	t20+p	5.03	10.40	~APO	0.20	0.83
t07+3	5.12	12.03	~APO	5.07	13.47	t36-3	0.18	0.42
~APO	24.32	25.61	t21-3	0.11	0.23	t36+P	0.78	1.87
h01-3	0.37	0.73	t21+3	2.54	8.75	~APO	0.39	0.69
h01+3	1.74	5.61	~APO	7.46	10.40	t37-3	0.34	0.79
~APO	0.22	0.99	t22-3	0.15	0.32	t37+3	4.21	10.35
d01-3	0.20	0.47	t22+3	1.62	5.31	~APO	14.16	14.61
d01+1	27.98	28.29	~APO	1.20	2.59	t38-3	0.28	0.67
~APO	1.55	3.60	t23-3	0.11	0.21	t38+3	3.70	8.70
t08-3	0.08	0.15	t23+3	2.34	7.21	~APO	8.76	9.70
t08+3	2.69	6.70	~APO	2.62	3.55	t39-3	0.16	0.36
~APO	1.89	3.44	t24-3	0.11	0.23	t39+3	3.34	8.40
r01-3	0.14	0.31	t24+3	1.20	3.04	~APO	1.73	2.52
r01+1	0.16	0.47	~APO	3.03	6.64	t40-3	0.10	0.22
~APO	1.94	4.34	t25-3	0.32	0.80	t40+p	0.43	1.09
t09-3	0.16	0.37	t25+3	1.90	4.94	~APO	49.72	51.36
t09+3	1.78	4.03	~APO	1.08	2.26	t41-3	1.46	3.41
~APO	0.12	0.26	t26-3	0.14	0.34	t41+p	5.29	7.95
t10-3	0.13	0.26	t26+3	3.29	7.96	~APO	4.42	12.88
t10+3	1.76	5.28	~APO	1.82	2.85	e03-3	0.28	0.67
~APO	1.15	2.76	t27-3	0.21	0.44	e03+1	1.14	2.89
t11-3	0.39	0.94	t27+3	3.80	9.19	~APO	1.32	3.01
t11+3	2.45	5.50	~APO	2.38	3.57	t42-3	0.09	0.20
~APO	0.29	0.74	t28-3	0.15	0.31	t42+p	3.73	6.10
t12-3	0.15	0.33	t28+3	3.89	9.49	~APO	2.68	7.05
t12+3	2.79	6.41	~APO	3.32	4.64	t43-3	0.12	0.29
~APO	1.77	3.59	t29-3	0.15	0.33	t43+P	1.33	2.75
t13-3	0.42	1.02	t29+3	5.35	12.50	~APO	2.86	7.21
t13+3	2.74	6.17	~APO	5.43	8.04	t44-3	0.11	0.22
~APO	0.65	1.56	t30-3	0.15	0.35			
t14-3	0.17	0.33	t30+3	5.19	12.38			

trajectory changes, anomalies, or for an extended mission. The ΔV cost of T2002-01 is greater and leaves a margin of 115 m/s.[4] The reduction in ΔV margin is dominated by the changes in SOI, PRM, PTM, and ODM.

The probe mission recovery requires trajectory changes that are essentially localized to the beginning of the tour. This localization carries over to the ΔV margin estimates, where it is seen that the reduction in mission ΔV margin is approximately equal to the deterministic rise in maneuver ΔV.

The new location of the probe mission has cost ΔV but likely has a side-effect of improved delivery statistics.[21] The new probe mission comes after two Titan encounters which provide an excellent opportunity for improving estimates of Titan's ephemeris. Furthermore, the higher Titan flyby altitude has eliminated the need for an ODM clean-up maneuver, reducing some risk associated with the probe data relay sequence.

Conclusion

The HRTF changes to the Cassini tour have resulted in a new tour, T2002-01, that modifies the beginning of the T18-5 tour. The T1 and T2 flybys of T18-5 have been replaced with three flybys (Ta, Tb, and Tc) in T2002-01 and the T18-5 tour is returned to on the T3 flyby. This preserves the science of Cassini tour while allowing a distant flyby for the Huygens probe delivery.

Delivery of the probe on a distant flyby reduces the Doppler shift of the probe relay signal. This allows the receiver onboard Cassini to maintain link with the probe throughout the probe mission.

These changes to the Cassini tour have reduced the mission margin from 210 m/s to 115 m/s, and have resulted in an additional Titan flyby. There have been small ripple effects due to the trajectory changes throughout the tour, but few science observations have been degraded and some have improved. With this redesign, Cassini-Huygens will be able to meet all of its science objectives in spite of the receiver anomaly.

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Appendix: B-plane Description

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "*B*–plane" coordinates[14] (see Figure 7). The B-plane is a plane passing through the planet center and perpendicular to the asymptote of the incoming trajectory (assuming 2 body conic motion). The "B-vector" is a vector in that plane, from the planet center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target planet had no mass and did not deflect the flight path. Coordinates are defined by three orthogonal unit vectors, ***S***, ***T***, and ***R*** with the system origin at the center of the target body. The ***S*** vector is parallel to the spacecraft V_∞ vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). ***T*** is arbitrary, but is typically specified to lie in the ecliptic plane (the mean plane of the Earth's orbit), or in a body equatorial plane. Finally, ***R*** completes an orthogonal triad with ***S*** and ***T***.

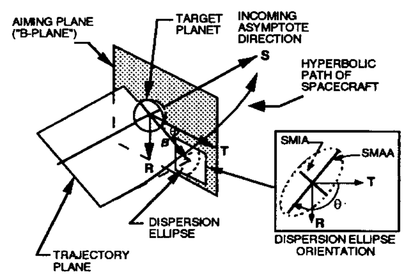

Figure 7: Aim Plane Coordinate System

Trajectory errors in the B-plane are often characterized by a one–sigma dispersion ellipse, shown in Figure 7. SMAA and SMIA denote the semi–major and semi–minor axes of the ellipse; q 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 encounter 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_∞ vector.

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