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ADDITION OF A LOW ALTITUDE TETHYS FLYBY TO THE NOMINAL CASSINI TOUR

Brent Buffington[†*], Nathan Strange[†], Rodica Ionasescu[†]

Of the eight Saturnian icy satellites, all but Mimas and Tethys had low altitude targeted flybys during the 4-year primary Cassini spacecraft tour. In November 2004, the existence of a potential low-altitude Tethys flyby was discovered; this low-altitude flyby, added to the nominal tour in March 2005, corresponded to a 1500 km non-targeted periapsis altitude on September 24, 2005 with an associated Δv cost of approximately 8 m/s. This memo details the methods used to determine the Rev-15 non-targeted Tethys flyby altitude, driven by navigational requirements and operational constraints, in addition to several trajectory modifications implemented to reduce total Δv costs, and in some cases, render simultaneous increases in scientific return.

INTRODUCTION

The 4-year nominal Cassini spacecraft tour of the Saturnian system, the most complex gravity-assist tour ever flown, consists of 45 targeted Titan flybys and eight targeted icy satellite flybys (including a pre-Saturn Orbital Insertion (SOI) Phoebe flyby) [1]. In addition to scientific importance, Titan flybys are needed to manipulate the Cassini spacecraft orbital geometry required to meet diverse scientific objectives. This stems from the fact that Titan is the only Saturnian satellite sufficient in mass to provide useful gravity-assists[††]. As a result, targeted icy satellite flybys must be incorporated in Titan-to-Titan transfers if and when desirable icy satellite flyby altitudes coincide [2,3]. This constraint renders targeted icy satellite flybys difficult to obtain, and based on nominal reference trajectory statistics, requires an average Δv cost of approximately 18 m/s per encounter [4].

Flybys in which the satellite relative aimpoints[**] are controlled with maneuvers are referred to as "targeted" flybys [5,6], and include all Titan flybys less than 11,000 km (and 60,000 km probe delivery flyby, Titan-C), and icy satellite flybys under a few thousand km (except 03En). In the case of Titan, the aimpoints are primarily dictated by the required trajectory modification (orbit orientation and inclination profile) imparted by the corresponding Titan gravity assist [5]. As a result, the flyby aimpoints must be tightly controlled to minimize flyby errors, which in turn minimize perturbations to the reference trajectory that must be corrected with maneuvers. In the case of the icy satellites, gravitational effects are diminutive, allowing some freedom[‡] in choosing

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[††] Titan is over 58 times as massive as Saturn's second largest moon, Rhea. A single 950 km Titan flyby provides a gravity assist Δv of approximately 800 m/s.

[**] See Appendix A.

[‡] For a given icy satellite flyby, a Δv-optimal set of flyby parameters exist. The "freedom" to vary the flyby parameters (to increase scientific return) is usually associated with a Δv cost.

specific flyby altitudes and B-plane angles. However, once specified, control of all targeted flyby aimpoints is necessary in order to achieve scientific objectives.

Conversely, flybys with no explicitly defined flyby parameters, and hence no maneuver aimpoint control, are referred to as "non-targeted" flybys. Consequently, periapsis times and altitudes shift with each reference trajectory update. Non-targeted flybys are important for global satellite imaging [6], and typically have periapsis altitudes greater than that defined for targeted flybys.

Of the eight Saturnian icy satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus, and Phoebe), all but Mimas and Tethys have low altitude targeted flybys in the primary mission. Hence, one of the primary goals to meet icy satellite scientific objectives [7] in the extended mission would be to perform low altitude flybys of Tethys and/or Mimas.

While investigating the feasibility/existence of low Δv cost trajectory options to reduce the September 23, 2005 E-ring crossing impact probability (most dangerous ring crossing, other than SOI, during the Cassini spacecraft's 4-year primary mission), the existence of a potential low-altitude Tethys flyby was discovered [8].

This paper details the methods used to determine the minimum non-targeted Tethys flyby altitude, driven by navigational requirements and operational constraints, in addition to several modifications implemented to reduce total Δv costs, and in some cases, render simultaneous increases in scientific return.

T7-T8 TRAJECTORY SEGMENT

A simplified[†] graphical depiction of the 041210 reference trajectory Titan-7 (T7) to Titan-8 (T8) localized sequence of events is illustrated in Figure 1 and outlined in Table 1. The near equatorial (inclination $\approx 0.3°$), non-resonant transfer between T7 and T8 consists of two targeted flybys, Hyperion-1 (H1) and Dione-1 (D1), which had corresponding flyby altitudes of 1010 km and 500 km respectively. In addition, a 29,800 km non-targeted flyby (15Te[*]) exists between OTM-034 and H1. As previously mentioned, Rev-15 E-ring impact probability variation studies revealed the existence of a potential low altitude Tethys flyby. Further analysis revealed this low-altitude flyby could be arbitrarily lowered while incurring reasonable Δv costs (Fig. 2).

While investigating lower Tethys flybys, a number of constraints were imposed during the optimization process: 1) H1, D1, and Enceladus-3 (E3) flyby altitudes and B-plane angles were fixed to the 041210 reference values, 2) the T7 flyby altitude was fixed to 1025 km [9], 3) all 950 km Titan flyby altitudes were fixed, 4) due to operational time constraints, flyby parameters (periapsis altitude, B-plane angle, and time of closest approach (TCA)) of targeted flybys prior to, and including T6, were fixed, and 5) trajectory modifications could not increase Rev-15 dust impact probabilities. The remaining targeted flybys were permitted to deviate from their nominal 041210 values.

[†] Mimas and Rhea orbits are omitted for simplicity.

[*] Non-targeted flyby naming convention: Orbit revolution number (incremented at apoapsis) followed by the first two letters of the satellite.

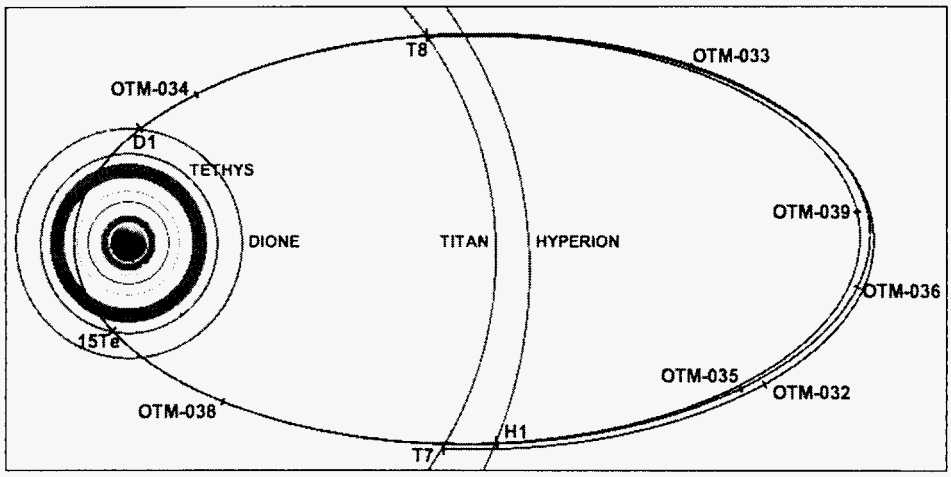

Figure 1: 041210 reference trajectory T7 – T8 segment events viewed from Saturn's North Pole. Note: Only deterministic maneuver locations shown with the exception of OTM-034.

Table 1: T7 – T8 segment events.

Event	Rev	Date (ET)	Description
T7/14Ti		**07-Sep-2005 08:01:50**	**Outbound 1025 km targeted Titan flyby**
OTM-032	14	10-Sep-2005 17:10:04	T7 Clean-up maneuver (T7 + 3d)
OTM-033		19-Sep-2005 16:41:04	Rev-14 apoapsis maneuver
OTM-034		*23-Sep-2005 07:46:04*	*Statistical H1 approach maneuver*
15Te		**24-Sep-2005 01:37:13**	**Outbound 29,800 km non-targeted flyby**
H1/15Hy	15	**26-Sep-2005 01:47:14**	**Outbound 1000 km targeted Hyperion flyby**
OTM-035		28-Sep-2005 16:12:04	H1 Clean-up maneuver (H1 + 3d)
OTM-036		01-Oct-2005 13:32:04	Rev-15 apoapsis maneuver
D1/16Di		**11-Oct-2005 18:00:44**	**Inbound 500 km targeted Dione flyby**
OTM-038	16	12-Oct-2005 16:46:04	D1 Clean-up maneuver (D1 + 1d)
OTM-039		21-Oct-2005 14:59:04	Rev-16 apoapsis maneuver
T8/17Ti	17	**28-Oct-2005 04:05:01**	**Inbound 1458 km targeted Titan flyby**

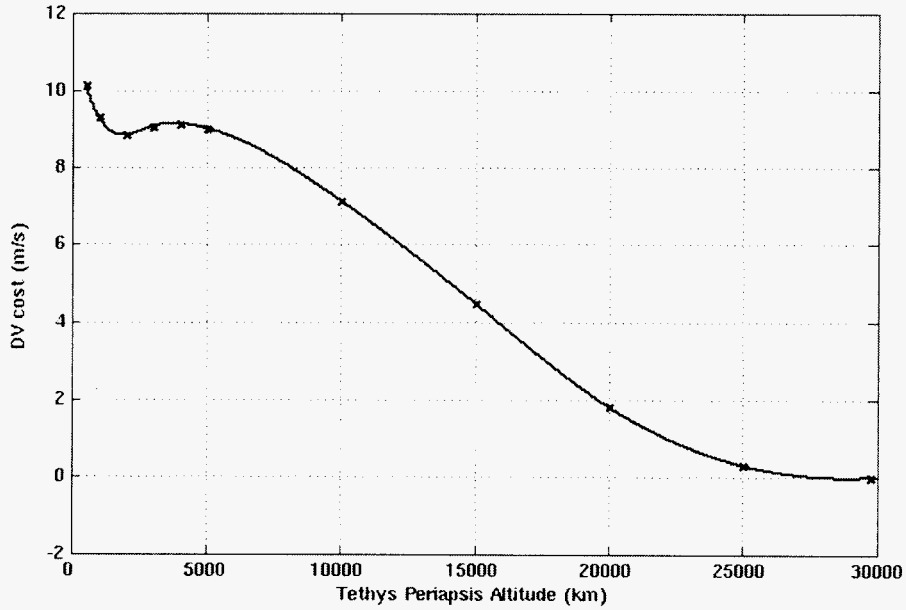

Figure 2: Optimized Δv cost associated with lowering the 15Te flyby altitude.

NAVIGATIONAL REQUIREMENTS

In general, delivery of the Cassini spacecraft to the targeted encounter aimpoints defined by the current reference trajectory is accomplished through a three maneuver per encounter strategy[‡] in which the first maneuver is a post-flyby clean-up maneuver, the second a near apoapsis maneuver, and the last a pre-flyby approach maneuver. The clean-up maneuver (approximately three days after an encounter) utilizes a chained two-impulse maneuver strategy, which couples the first and second maneuvers within each trajectory leg and chains them across a specified number[*] of downstream encounters while inhibiting final flyby aimpoint variation(s) [1,11]. The near apoapsis maneuver is usually a trajectory-shaping maneuver and in many cases has a significant deterministic component. Lastly, the statistical approach maneuver (approximately three days prior to an encounter) is utilized to negate maneuver execution errors and orbit determination (OD) uncertainties inherent to the apoapsis maneuver. In addition, the approach maneuver takes advantage of improved OD solutions.

As can be seen in Table 2, approximately two days separate 15Te with H1; Based solely on event timing outline in the maneuver strategy, it is operationally impossible to make 15Te a targeted flyby. There is simply not enough time to converge a post-15Te O.D. solution, and design, uplink, and perform a maneuver between 15Te and H1 that would clean-up 15Te flyby errors by targeting H1 aimpoints. However, by using OTM-032 and OTM-033, the correct geometry can be set-up to include a low altitude untargeted Rev-15 Tethys flyby with targeted flyby characteristics.

MINIMUM FLYBY ALTITUDE DETERMINATION

The main concern with lowering 15Te is the flyby occurs after OTM-034 (last maneuver to fine-tune H1 targets) and will therefore introduce additional errors in the trajectory that cannot be corrected. This will directly affect predicted H1 pointing values. As defined by the Cassini Navigation Plan [1], Navigation must provide 1-sigma radial pointing prediction accuracies of 0.79 mrad at 30,000 km (altitude), and 1.02 mrad at a 20,000 km. Prior to lowering 15Te, covariance analysis 20,000 km and 30,000 km pointing uncertainties for H1 were 0.46 and 0.30 mrad respectively [12]. Since science observations/measurements are contingent on meeting pointing requirements, the minimum Tethys flyby altitude associated with maintaining H1 pointing predictions needed to be determined.

To solve this problem with the highest sense of confidence, numerous full-scale OD covariance analyses, using different spacecraft trajectories (each gradually stepping down 15Te periapsis) would have to be carried out until H1 pointing requirements were not met. However, a single covariance analysis, due to the extensive/complex initial set-up and inputs needed from maneuver analysts, trajectory analysts, and O.D., requires approximately two weeks to complete. Due to the limited time that remained to introduce changes to the spacecraft sequence(s), this was an impractical strategy. Therefore, a conservative, first-order analysis (using previous covariance

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[‡] Delivery of ESA's Huygens Probe during the Titan-B to Titan-C transfer did not adhere to the general three-maneuver strategy [10].

[*] Segment dependent number of encounters determined through parametric Monte Carlo simulations (minimizes Δv).

analysis statistics, patched conics, and the time-to-go approximation), was first performed to estimate a minimum Tethys flyby altitude. The purpose of this simpler study was to prove/disprove 15Te could be significantly lowered while maintaining H1 pointing requirements, and hence, would/wouldn't substantiate the additional work needed to produce an update covariance analysis and spacecraft sequence modification(s).

Though Tethys' gravitational parameter is small (μ = 41.2116 km^3/s^2), gravitational perturbations, which effectively amplify any spacecraft flyby position errors, are the primary source of errors introduced into the trajectory. For a given Tethys flyby altitude, the trajectory design optimization process accounts for the bending angle and the Δv (Eq. 1) induced by the Tethys flyby,

$$\Delta v_{\text{nominal}} = \frac{2\mu v_\infty}{\mu + r_p v_\infty^2} \tag{1}$$

where v_∞ is Cassini's Tethys-relative hyperbolic excess velocity, and r_p is the radius of periapsis [13]. However, due to spacecraft (OD uncertainties and OTM-034 maneuver execution errors) and satellite position uncertainties, the actual flyby periapsis will differ (high/low) from the reference flyby periapsis by an amount δr; the corresponding Δv associated with the actual flyby is given by Eq. 2. By taking the difference of Eqs. (1) and (2), the quantity of concern, namely the Δv input to the system which cannot be corrected prior to H1, can be calculated (Eq. 3).

$$\Delta v_{hight/low} = \frac{2\mu v_\infty}{\mu + (r_p \pm \delta r) v_\infty^2} \tag{2}$$

$$\delta\Delta v = \left|\Delta v_{\text{nominal}} - \Delta v_{\text{high/low}}\right| \tag{3}$$

To obtain an estimate for δr, statistics from the T2002-01 covariance analysis (030608 OPNAV schedule)[†] were utilized (Fig. 3) [12]. More specifically, the semi-major axis (SMAA) of the 1-sigma B-plane error ellipse mapped to H1 at the OTM-034 data cut-off (DCO), 9.2 km, was used for δr. This strategy of implementing the H1 maximum error ellipse component as the deviation in 15Te periapsis proved conservative for the following reasons: 1) implies a worst-case error ellipse orientation – periapsis vector aligned with the SMAA, 2) the uncertainty statistics are mapped to H1 but are used at 15Te (less time for spacecraft uncertainties to propagate), and, 3) satellite ephemeris uncertainties are lower for Tethys (Tethys and Hyperion ephemeris uncertainties were 3.3 km and 4.0 km respectively) [1].

Letting δr = 9.2 km, v_∞ = 9.01 km/s, and r_{TETHYS} = 529.8 km in Eq. (4), $\delta\Delta v$ was computed as a function of the 15Te flyby altitude (Fig. 4).

[†] Herein, the T2002-1 covariance analysis, which utilizes the 030608 OPNAV schedule, will simply be referred to as the Navigation Plan covariance analysis.

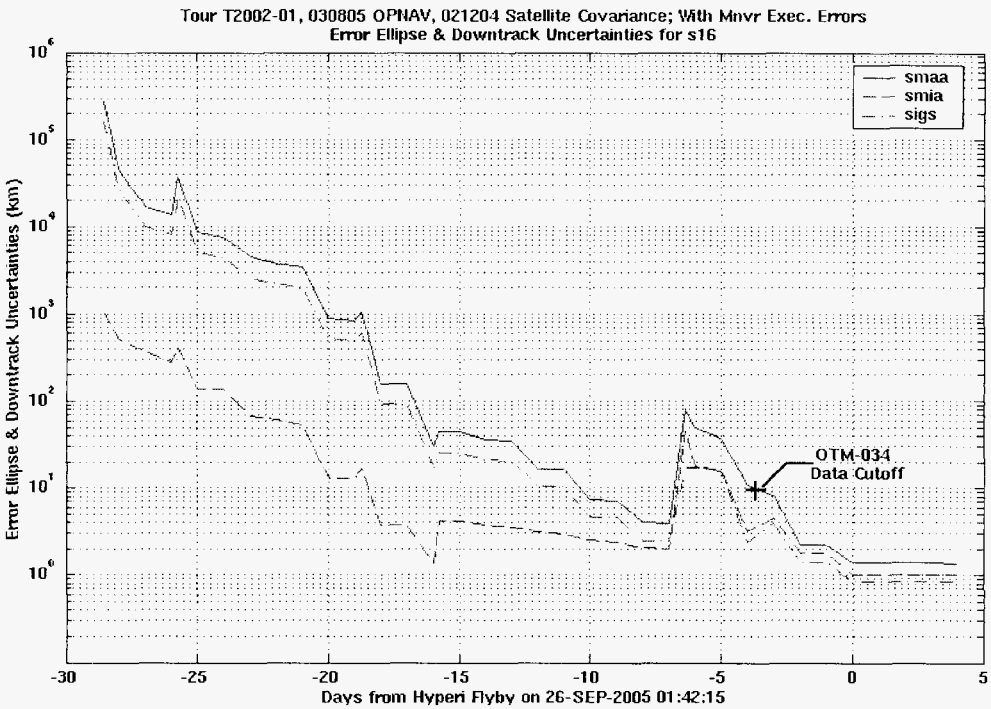

Figure 3: Updated T2002-01 B-plane error ellipse and downtrack uncertainties mapped the H1. Note: SMAA – semi-major axis, SMIA – semi-minor axis, SIGS – out-of-plane component.

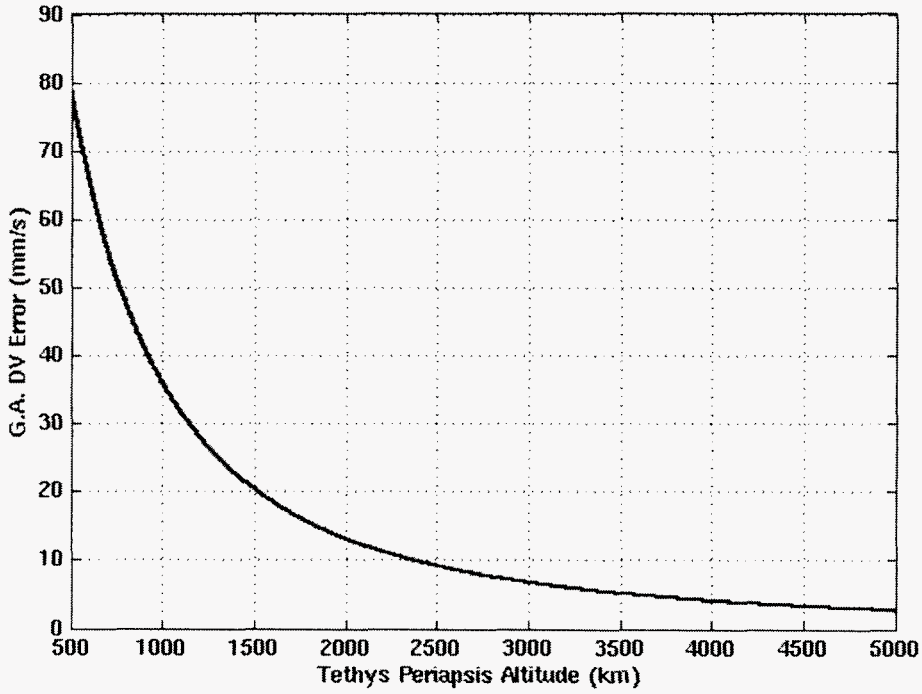

Figure 4: Δv deviations associated with a 9.2 km flyby altitude error as a function of nominal flyby altitude. Note: Blue – "high" relative flyby, red – "low" relative flyby. (Blue curve on top of red)

The next step was to estimate the H1 B-plane uncertainties associated with the Tethys flyby $\delta\Delta v$. Using the time-to-go approximation (Eq. 4), where t is time, and varying Δv, the deviations in the B-plane were computed as a function of $\delta\Delta v$ [14]. The scale factor, 86.4, was utilized so ΔB can be expressed in kilometers, Δv in m/s, and t in days.

$$\Delta B = 86.4(t)\delta\Delta v \tag{4}$$

Taking the root-sum-square (RSS) of the linear time-to-go B-plane variation function and 9.2 km (largest H1 uncertainty inherent to the system) produced the total estimated H1 B-plane uncertainties as a function of Δv (Fig. 5).

The final piece of information needed to establish the estimated minimum 15Te flyby altitude was the maximum tolerance of the total B-plane uncertainties that still maintained the H1 pointing requirements. Based on previous covariance analysis experience with respect to H1, it was believed H1 pointing requirements would most likely be met if the total B-plane uncertainties were kept at or below 10 km. Extrapolating the Δv value corresponding to 10 km from Figure 6 (23.2 mm/s), and applying the Δv value to Figure 4 (worst case "low" flyby used, i.e. larger $\delta\Delta v$ for a given periapsis altitude), the estimated minimum Tethys flyby altitude was determined to be approximately 1400 km.

Figure 7 exhibits a sample set of potential Tethys groundtracks associated with reasonable Δv costs; the uppermost red groundtrack represents the nominal 041210 groundtrack and the lower-most blue track represents a 1000 km periapsis altitude (slightly lower than first-order approximation estimates navigationally possible). Of particular interest are flyby altitudes ranging between 1000 – 2000 km, which pass directly over or near Ithaca Chasm, and would provide science a unique opportunity to fully investigate the subsurface composition of Tethys.

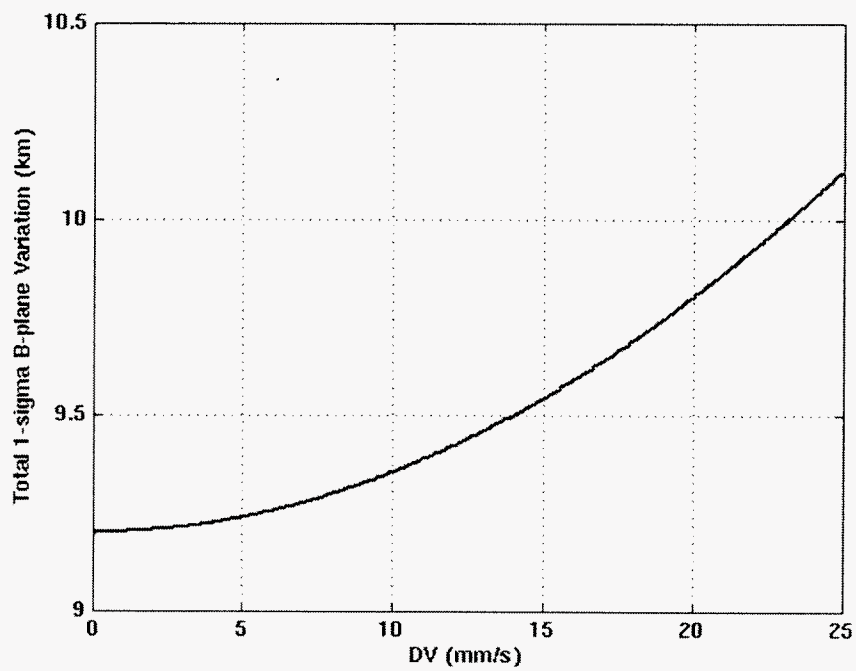

Figure 5: Total H1 B-plane variation as function of Δv.

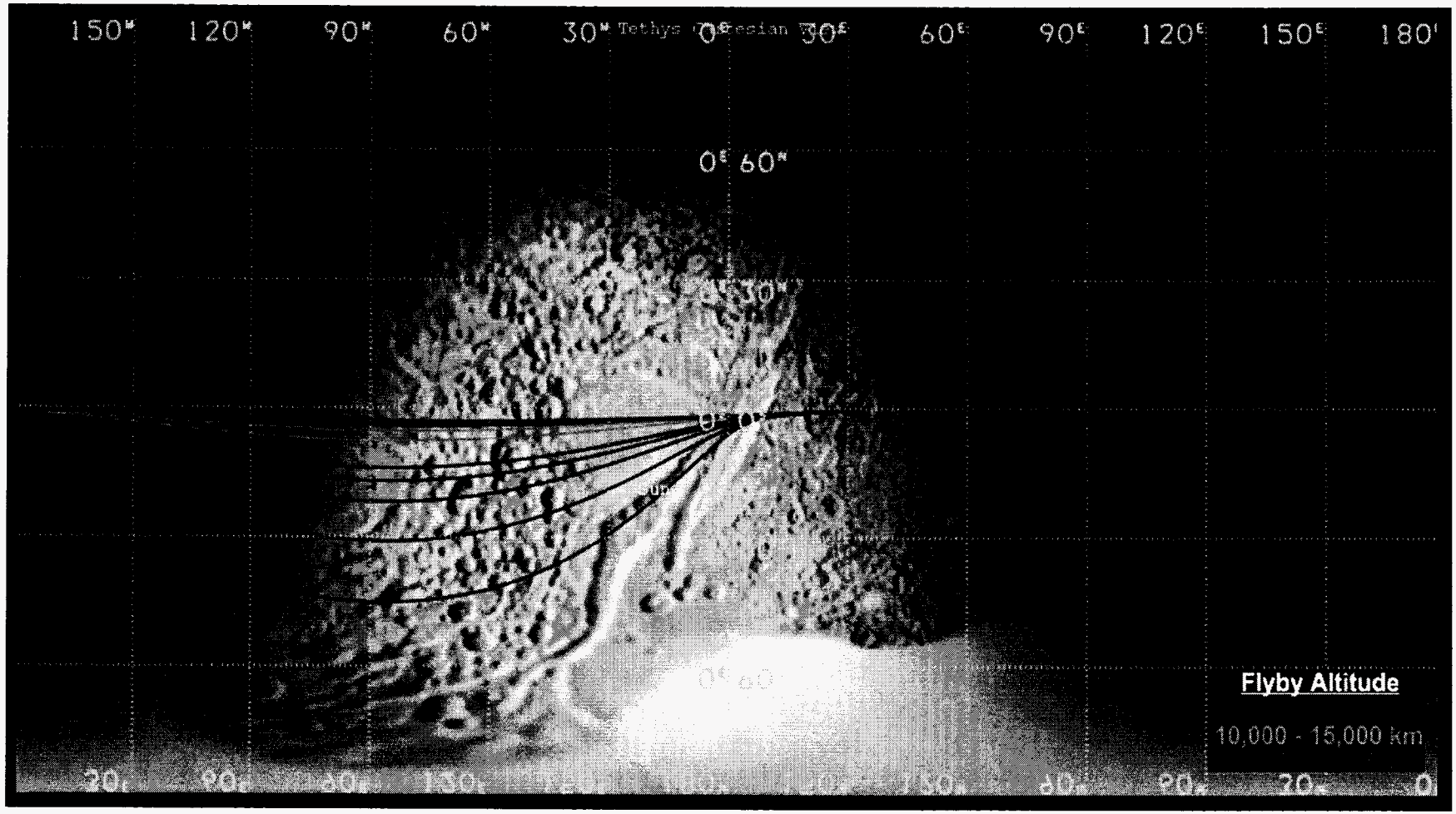

Figure 7: Tethys groundtracks for varying flyby altitudes.

OPERATIONAL CONSTRAINTS

To quantify trajectory changes induced by lowering 15Te to present to the Cassini Project (seeking approval), a preliminary 2000 km 15Te flyby altitude was chosen (Tables 2 & 3). This choice exercised conservatism from a navigation point of view, corresponded to a local Δv cost minima (Fig. 2), and also exhibited greatly improved scientific return with respect to the nominal 29,800 km flyby.

As can be seen in Tables 2 and 3, significant targeted flyby time shifts from T7 through T35 and Saturn relative periapsis time shifts from Rev-14 through Rev-37 resulted from the trajectory modification, with the largest time shifts (> 10 minutes) highlighted in red. These shifts are a direct result of the trajectory re-optimization process; all post-T6 downstream targeted flyby parameters (excluding previously defined exceptions) were free to vary in order to minimize the cost function – total tour Δv. However, while ideally a minimum Δv solution would be chosen, operational constraints significantly dictate the extent/feasibility of potential trajectory modifications.

The optimization of science return requires numerous detailed sequence iterations between the different Cassini instrument teams. Much of these trades rely heavily on knowing portions of the trajectory well in advance in order to fully understand what (and when) specific orbital geometries will be available. Hence, when introducing trajectory modifications, implications of altitude and timing shifts (with particular emphasis placed on Saturn periapses), which include increased/decreased scientific return, the potential amount of time and work needed to perform sequence updates (in some cases, construction of entirely new sequences), and risks associated with the limited time available for sequence re-verification/testing, must be weighed against Δv costs.

In an attempt to minimize downstream effects caused by the lowering of 15Te, specific Titan flybys, in addition to all subsequent Titan flybys, were nominally constrained in the trajectory optimization process. The Δv cost associated with each case is summarized in Figure 8. In other words, Figure 8 conveys the additional Δv cost (in addition to the Δv needed to lower 15Te) required to circumvent downstream "ripples" with respect to the nominal tour by a specified flyby. As can be seen in Figure 8, fixing T8 and all post-T8 flybys is clearly cost prohibitive, but the remaining options were practical. After collaboration with navigators, scientists, mission and science planners, instrument teams, etc., the project decided to fix T9 and all subsequent targeted flybys. The resultant targeted flyby time/altitude shifts and Saturn relative periapsis time shifts are summarized in Tables 4 & 5. The decision reduced the spacecraft sequence workload (i.e. minimized time shifts) at the expense of Δv, but due to Δv savings associated with moving OTM-038, total Δv costs remained low.

Table 2: Targeted flyby altitude and timing shifts associated with a 2000 km 15Te flyby.

Encounter	Body	In/Out	Date (UTC)	Alt. [km]	ΔH (km) 041210	Δt (mm:ss) 041210
E2 / 11En	Enceladus	I	14-Jul-2005 19:57:59	1000	0	00:00
T6 / 13Ti	Titan	O	22-Aug-2005 08:53:37	3738	-20	00:00
T7 / 14Ti	Titan	O	07-Sep-2005 08:11:51	1025	0	**11:05**
15Te	**Tethys**	**O**	**24-Sep-2005 02:41:25**	**2000**	**-27771**	**65:14**
H1 / 15Hy	Hyperion	I	26-Sep-2005 02:25:31	1010	0	**39:21**
D1 / 16Di	Dione	I	11-Oct-2005 17:52:23	500	0	-07:17
T8 / 17Ti	Titan	I	28-Oct-2005 04:03:13	1430	-21	-00:44
R1 / 18Rh	Rhea	I	26-Nov-2005 22:33:22	500	0	-04:11
T9 / 19Ti	Titan	O	26-Dec-2005 19:39:41	10124	-284	**40:11**
T10 / 20Ti	Titan	I	15-Jan-2006 11:40:32	2000	-43	-00:55
T11 / 21Ti	Titan	O	27-Feb-2006 09:03:11	1772	-41	**37:52**
T12 / 22Ti	Titan	I	19-Mar-2006 00:03:01	1910	-41	-02:56
T13 / 23Ti	Titan	O	30-Apr-2006 21:34:17	1812	-42	**36:02**
T14 / 24Ti	Titan	I	20-May-2006 12:13:01	1879	0	-05:11
T15 / 25Ti	Titan	O	02-Jul-2006 10:08:02	1858	-48	**47:14**
T16 / 26Ti	Titan	I	22-Jul-2006 00:28:07	950	0	02:40
T17 / 28Ti	Titan	I	07-Sep-2006 20:16:01	950	0	03:13
T18 / 29Ti	Titan	I	23-Sep-2006 18:55:00	950	0	00:17
T19 / 30Ti	Titan	I	09-Oct-2006 17:29:52	950	0	04:20
T20 / 31Ti	Titan	I	25-Oct-2006 15:57:49	950	0	04:12
T21 / 35Ti	Titan	I	12-Dec-2006 11:41:33	950	0	04:08
T22 / 36Ti	Titan	I	28-Dec-2006 10:03:05	1500	0	01:03
T23 / 37Ti	Titan	I	13-Jan-2007 08:36:52	950	0	01:09
T24 / 38Ti	Titan	I	29-Jan-2007 07:14:12	2536	-191	00:38
T25 / 39Ti	Titan	O	22-Feb-2007 03:10:58	950	0	00:46
T26 / 40Ti	Titan	O	10-Mar-2007 01:47:42	950	0	00:50
T27 / 41Ti	Titan	O	26-Mar-2007 00:22:22	950	0	00:49
T28 / 42Ti	Titan	O	10-Apr-2007 22:56:54	950	0	00:29
T29 / 43Ti	Titan	O	26-Apr-2007 21:31:11	950	0	-00:18
T30 / 44Ti	Titan	O	12-May-2007 20:07:28	950	0	-00:11
T31 / 45Ti	Titan	O	28-May-2007 18:50:36	2424	-2	-00:13
T32 / 46Ti	Titan	O	13-Jun-2007 17:46:14	950	0	-00:17
T33 / 47Ti	Titan	O	29-Jun-2007 17:02:21	1944	0	-00:19
T34 / 48Ti	Titan	I	19-Jul-2007 00:38:20	1301	1	00:34
T35 / 49Ti	Titan	O	31-Aug-2007 06:34:39	3212	0	-00:18
I1 / 49Ia	Iapetus	O	10-Sep-2007 12:33:53	1226	-1	00:00
T36 / 50Ti	Titan	O	02-Oct-2007 04:54:04	950	0	00:06
T37 / 52Ti	Titan	O	19-Nov-2007 00:58:27	950	0	00:05
T38 / 53Ti	Titan	O	05-Dec-2007 00:06:22	1300	0	00:06
T39 / 54Ti	Titan	O	20-Dec-2007 22:53:01	950	0	00:05
T40 / 55Ti	Titan	O	05-Jan-2008 21:25:01	950	0	00:05
T41 / 59Ti	Titan	O	22-Feb-2008 17:39:09	950	0	00:01
E3 / 61En	Enceladus	I	12-Mar-2008 19:06:40	100	0	00:00
T42 / 62Ti	Titan	O	25-Mar-2008 14:35:08	950	0	00:00
T43 / 67Ti	Titan	O	12-May-2008 10:10:01	950	0	00:00
T44 / 69Ti	Titan	O	28-May-2008 08:33:14	1348	0	00:00

Table 3: Saturn periapsis variations associated with a 2000 km 15Te flyby.

Rev	Periapsis				Period	ΔPeriod	Inclination	ΔIncl.
	Date (UTC)	Δt (mm:ss)	Radius (RS)	ΔRp (km)	(days)	(days)	(deg)	(deg)
11	14-Jul-2005 22:11:58	00:01	3.61	-6	17.931	0	21.819	0
12	02-Aug-2005 05:26:02	00:09	3.61	0	18.111	0	21.822	0
13	20-Aug-2005 11:13:41	-00:05	3.60	60	18.478	0	21.921	-0
14	05-Sep-2005 11:49:50	**14:12**	2.76	-995	16.525	0.005	16.139	-0
15	23-Sep-2005 21:34:59	**52:51**	3.00	-3220	19.205	0.057	0.288	0.011
16	12-Oct-2005 01:31:24	-07:52	3.00	-3081	19.207	-0.007	0.353	0.004
17	29-Oct-2005 22:42:30	-08:57	4.55	-3877	28.615	0.013	0.395	0.001
18	27-Nov-2005 11:16:43	-04:31	4.53	-2707	28.188	0.038	0.387	-0
19	24-Dec-2005 22:10:42	**47:30**	4.53	-2683	27.536	0.042	0.387	-0
20	17-Jan-2006 06:51:38	-06:40	5.53	-3130	39.095	0.041	0.381	0
21	25-Feb-2006 11:39:30	**43:48**	5.53	-3124	39.1	0.04	0.376	0
22	20-Mar-2006 19:55:57	-08:48	5.42	-3136	39.128	0.039	0.391	0
23	29-Apr-2006 00:40:42	**41:34**	5.42	-3136	39.132	0.043	0.375	0
24	22-May-2006 08:49:31	**-11:19**	5.38	-4118	38.9	-0.17	0.443	0
25	30-Jun-2006 13:57:47	**52:36**	5.38	-3383	39.159	0.056	0.396	-0
26	23-Jul-2006 21:42:36	-05:14	4.14	-3190	24.114	0.017	15.028	0.041
27	16-Aug-2006 20:49:48	-03:53	4.12	-3009	24.009	0.005	14.923	0.038
28	09-Sep-2006 17:33:28	-04:14	2.91	-2098	16.433	0.042	25.026	0.089
29	25-Sep-2006 19:25:22	-07:07	3.92	-2358	16.058	0.008	37.966	0.131
30	11-Oct-2006 22:48:00	-03:24	5.45	-2406	15.922	0.004	46.978	0.103
31	28-Oct-2006 00:11:28	-05:36	4.66	-2285	12.012	0.003	55.533	0.117
32	08-Nov-2006 23:58:39	-04:18	4.67	-2297	12.121	0.003	55.522	0.117
33	20-Nov-2006 23:01:38	-04:24	4.66	-2249	11.928	-0.001	55.553	0.115
34	02-Dec-2006 21:39:03	-04:45	4.66	-2255	11.822	-0.002	55.577	0.116
35	14-Dec-2006 23:56:39	**-21:19**	7.63	-5523	15.991	0.089	53.155	-0.15
36	31-Dec-2006 05:03:22	**-12:25**	9.75	-4112	15.9	0	56.698	-0.09
37	16-Jan-2007 12:52:18	**-14:41**	12.50	-4589	15.92	-0.001	59.384	-0.05
38	01-Feb-2007 09:57:07	01:48	15.58	133	18.071	-0.001	59.002	0.002
39	19-Feb-2007 11:48:04	00:44	15.58	133	18.074	0	59	0.002
40	07-Mar-2007 07:11:28	00:32	12.12	127	15.909	0	58.771	0.002
41	23-Mar-2007 12:02:12	00:33	9.67	103	15.898	0	56.204	0.003
42	08-Apr-2007 16:30:42	00:14	7.50	96	15.9	0	52.4	0.003
43	24-Apr-2007 20:12:19	-00:39	5.67	127	15.919	0.001	46.902	-0
44	10-May-2007 22:54:52	-00:25	4.22	84	15.992	0	39.084	0.001
45	27-May-2007 00:36:07	-00:24	3.18	66	16.193	0	28.155	0.003
46	12-Jun-2007 00:50:57	-00:25	2.71	48	16.479	0	18.38	-0
47	28-Jun-2007 01:01:56	-00:27	2.43	48	16.788	-0.001	2.237	1E-03
48	20-Jul-2007 19:51:31	00:43	5.31	72	39.666	-0.001	0.305	0
49	29-Aug-2007 13:09:55	-00:25	5.30	72	39.63	-0.001	0.299	0
50	30-Sep-2007 11:49:00	00:06	4.63	0	32.081	-0.001	6.233	0
51	24-Oct-2007 08:18:14	00:07	3.74	-6	23.978	0	4.959	0
52	17-Nov-2007 08:11:37	00:05	3.74	0	24.264	0	4.946	0
53	03-Dec-2007 07:43:06	00:06	2.51	0	16.679	0	12.73	0.001
54	19-Dec-2007 05:01:27	00:05	3.01	0	16.278	0	26.485	0
55	04-Jan-2008 00:43:07	00:05	3.97	6	16.01	0	37.967	0
56	15-Jan-2008 21:54:29	00:01	3.27	0	11.735	0	47.014	0
57	27-Jan-2008 20:27:52	-00:03	3.27	0	11.88	0	46.983	0
58	08-Feb-2008 19:20:45	-00:07	3.26	6	12.314	0	47.569	-0
59	20-Feb-2008 19:33:48	00:01	3.26	0	12.16	0	47.573	-0
60	02-Mar-2008 05:09:37	-00:00	3.75	0	10.502	0	56.736	-0
61	12-Mar-2008 20:57:06	00:00	3.75	0	10.732	0	56.714	0
62	23-Mar-2008 12:19:16	00:00	3.75	0	10.704	0	56.709	0
63	01-Apr-2008 20:24:20	-00:00	4.32	0	9.487	0	63.651	0
64	11-Apr-2008 10:24:51	-00:00	4.32	0	9.664	0	63.623	0
65	20-Apr-2008 23:47:02	-00:00	4.32	0	9.477	0	63.643	0
66	30-Apr-2008 12:55:41	-00:00	4.31	0	9.576	0	63.632	-0
67	10-May-2008 02:14:02	00:00	4.31	0	9.593	0	63.627	-0
68	17-May-2008 23:45:52	-00:00	3.26	0	7.926	0	69.972	0
69	25-May-2008 22:56:43	-00:00	3.26	0	8.057	0	69.956	-0
70	01-Jun-2008 22:22:42	-00:00	2.70	0	7.144	0	75.427	-0
71	09-Jun-2008 01:10:11	-00:00	2.70	0	7.15	0	75.426	0
72	16-Jun-2008 03:45:53	-00:00	2.68	0	7.252	0	75.458	0
73	23-Jun-2008 06:20:32	-00:00	2.68	0	7.052	0	75.475	0
74	30-Jun-2008 08:50:26	-00:01	2.68	0	7.338	0	75.475	-0
75	07-Jul-2008 11:19:06	-00:01	2.68	0	7.013	0	75.497	0

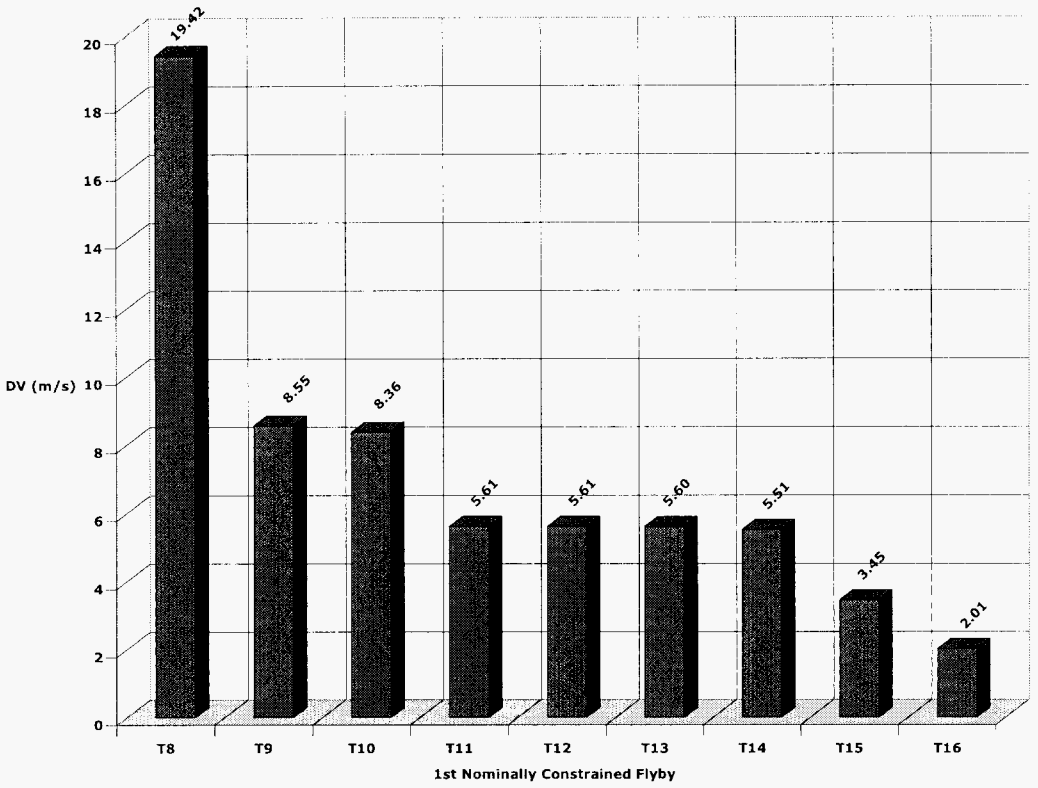

Figure 8: Additional Δv required to "tie-down" the modified trajectory at a specific Titan flyby and all subsequent targeted flybys.

Table 4: Targeted flyby altitude and timing shifts associated with a 2000 km 15Te flyby and constraining T9 and all subsequent targeted flybys to 041210 reference aimpoints.

Encounter	Body	In/Out	Date (UTC)	Alt. [km]	ΔH (km) 041210	Δt (mm:ss) 041210
E2 / 11En	Enceladus	I	14-Jul-2005 19:57:59	1000	0	00:00
T6 / 13Ti	Titan	O	22-Aug-2005 08:53:37	3734	-24	00:00
T7 / 14Ti	Titan	O	07-Sep-2005 08:11:27	1025	0	10:41
15Te	**Tethys**	**O**	**24-Sep-2005 02:41:06**	**2000**	**-27771**	**64:55**
H1 / 15Hy	Hyperion	I	26-Sep-2005 02:25:40	1010	0	39:30
D1 / 16Di	Dione	I	11-Oct-2005 17:53:00	500	0	-06:40
T8 / 17Ti	Titan	I	28-Oct-2005 04:05:17	1369	-83	01:20
R1 / 18Rh	Rhea	I	26-Nov-2005 22:37:50	500	0	00:17
T9 / 19Ti	Titan	O	26-Dec-2005 18:59:30	10409	0	00:00
T10 / 20Ti	Titan	I	15-Jan-2006 11:41:27	2043	0	00:00
T11 / 21Ti	Titan	O	27-Feb-2006 08:25:19	1813	0	00:00
T12 / 22Ti	Titan	I	19-Mar-2006 00:05:57	1951	0	00:00
T13 / 23Ti	Titan	O	30-Apr-2006 20:58:15	1855	0	00:00
T14 / 24Ti	Titan	I	20-May-2006 12:18:12	1879	0	00:00
T15 / 25Ti	Titan	O	02-Jul-2006 09:20:48	1906	0	00:00
T16 / 26Ti	Titan	I	22-Jul-2006 00:25:27	950	0	00:00
T17 / 28Ti	Titan	I	07-Sep-2006 20:12:48	950	0	00:00
T18 / 29Ti	Titan	I	23-Sep-2006 18:54:43	950	0	00:00
T19 / 30Ti	Titan	I	09-Oct-2006 17:25:32	950	0	00:00
T20 / 31Ti	Titan	I	25-Oct-2006 15:53:37	950	0	-00:00
T21 / 35Ti	Titan	I	12-Dec-2006 11:37:25	950	0	00:00
T22 / 36Ti	Titan	I	28-Dec-2006 10:02:02	1500	0	00:00
T23 / 37Ti	Titan	I	13-Jan-2007 08:35:43	950	0	00:00
T24 / 38Ti	Titan	I	29-Jan-2007 07:13:34	2726	0	00:00
T25 / 39Ti	Titan	O	22-Feb-2007 03:10:12	950	0	00:00
T26 / 40Ti	Titan	O	10-Mar-2007 01:46:52	950	0	00:00
T27 / 41Ti	Titan	O	26-Mar-2007 00:21:33	950	0	00:00
T28 / 42Ti	Titan	O	10-Apr-2007 22:56:25	950	0	00:00
T29 / 43Ti	Titan	O	26-Apr-2007 21:31:29	950	0	00:00
T30 / 44Ti	Titan	O	12-May-2007 20:07:39	950	0	00:00
T31 / 45Ti	Titan	O	28-May-2007 18:50:49	2426	0	00:00
T32 / 46Ti	Titan	O	13-Jun-2007 17:46:31	950	0	00:00
T33 / 47Ti	Titan	O	29-Jun-2007 17:02:40	1944	0	00:00
T34 / 48Ti	Titan	I	19-Jul-2007 00:37:46	1300	0	00:00
T35 / 49Ti	Titan	O	31-Aug-2007 06:34:57	3212	0	00:00
I1 / 49Ia	Iapetus	O	10-Sep-2007 12:33:53	1227	0	00:00
T36 / 50Ti	Titan	O	02-Oct-2007 04:53:58	950	0	00:00
T37 / 52Ti	Titan	O	19-Nov-2007 00:58:22	950	0	00:00
T38 / 53Ti	Titan	O	05-Dec-2007 00:06:16	1300	0	00:00
T39 / 54Ti	Titan	O	20-Dec-2007 22:52:56	950	0	-00:00
T40 / 55Ti	Titan	O	05-Jan-2008 21:24:56	950	0	00:00
T41 / 59Ti	Titan	O	22-Feb-2008 17:39:08	950	0	00:00
E3 / 61En	Enceladus	I	12-Mar-2008 19:06:40	100	0	00:00
T42 / 62Ti	Titan	O	25-Mar-2008 14:35:08	950	0	00:00
T43 / 67Ti	Titan	O	12-May-2008 10:10:01	950	0	00:00
T44 / 69Ti	Titan	O	28-May-2008 08:33:14	1348	0	00:00

Table 5: Saturn periapsis variations associated with a 2000 km 15Te flyby and constraining T9 and all subsequent targeted flybys to 041210 reference aimpoints.

Rev	Periapsis				Period (days)	ΔPeriod (days)	Inclination (deg)	ΔIncl. (deg)
	Date (UTC)	Δt (mm:ss)	Radius (RS)	ΔRp (km)				
11	14-Jul-2005 22:11:59	00:01	3.61	-6	17.931	0	21.819	0
12	02-Aug-2005 05:26:15	00:21	3.61	-6	18.111	0	21.822	0
13	20-Aug-2005 11:13:31	-00:15	3.60	115	18.477	-0.001	21.92	-0.002
14	05-Sep-2005 11:48:56	**13:17**	2.76	-869	16.52	0	16.133	-0.007
15	23-Sep-2005 21:34:42	**52:34**	3.00	-3083	19.204	0.056	0.289	0.012
16	12-Oct-2005 01:32:03	-07:13	3.00	-2944	19.206	-0.008	0.354	0.005
17	29-Oct-2005 22:45:14	-06:12	4.58	-2093	28.854	0.252	0.391	-0.003
18	27-Nov-2005 11:21:28	00:14	4.58	12	28.177	0.027	0.389	0
19	24-Dec-2005 21:23:13	00:00	4.57	0	27.494	0	0.389	0
20	17-Jan-2006 06:58:17	00:00	5.58	0	39.054	0	0.381	0
21	25-Feb-2006 10:55:42	00:00	5.58	0	39.06	0	0.376	0
22	20-Mar-2006 20:04:45	00:00	5.48	0	39.089	0	0.391	0
23	28-Apr-2006 23:59:08	00:00	5.47	0	39.089	0	0.375	0
24	22-May-2006 09:00:49	00:00	5.45	0	39.07	0	0.443	0
25	30-Jun-2006 13:05:10	00:00	5.44	0	39.103	0	0.398	0
26	23-Jul-2006 21:47:50	00:00	4.19	0	24.097	0	14.987	0
27	16-Aug-2006 20:53:41	00:00	4.17	0	24.004	0	14.885	0
28	09-Sep-2006 17:37:42	-00:00	2.94	0	16.391	0	24.937	0
29	25-Sep-2006 19:32:28	-00:00	3.96	0	16.05	0	37.835	0
30	11-Oct-2006 22:51:24	-00:00	5.49	0	15.918	0	46.875	0
31	28-Oct-2006 00:17:04	00:00	4.70	0	12.009	0	55.416	0
32	09-Nov-2006 00:02:58	00:00	4.71	0	12.118	0	55.405	0
33	20-Nov-2006 23:06:01	00:00	4.70	0	11.929	0	55.437	-0.001
34	02-Dec-2006 21:43:48	-00:00	4.70	0	11.824	0	55.461	0
35	15-Dec-2006 00:17:57	00:00	7.72	0	15.902	0	53.304	0
36	31-Dec-2006 05:15:46	-00:00	9.82	0	15.9	0	56.785	0
37	16-Jan-2007 13:06:59	-00:00	12.57	0	15.921	0	59.437	0
38	01-Feb-2007 09:55:18	-00:00	15.57	0	18.072	0	59	0
39	19-Feb-2007 11:47:20	00:00	15.58	0	18.074	0	58.998	0
40	07-Mar-2007 07:10:57	00:00	12.12	0	15.909	0	58.769	0
41	23-Mar-2007 12:01:39	00:00	9.67	0	15.898	0	56.201	0
42	08-Apr-2007 16:30:28	00:00	7.50	0	15.9	0	52.397	0
43	24-Apr-2007 20:12:57	00:00	5.67	0	15.918	0	46.903	0
44	10-May-2007 22:55:17	00:00	4.22	0	15.992	0	39.083	0
45	27-May-2007 00:36:31	00:00	3.18	0	16.193	0	28.152	0
46	12-Jun-2007 00:51:22	00:00	2.71	0	16.479	0	18.381	0
47	28-Jun-2007 01:02:24	-00:00	2.43	0	16.789	0	2.236	0
48	20-Jul-2007 19:50:48	00:00	5.31	0	39.667	0	0.305	0
49	29-Aug-2007 13:10:19	00:00	5.30	0	39.631	0	0.299	0
50	30-Sep-2007 11:48:54	00:00	4.63	0	32.082	0	6.233	0
51	24-Oct-2007 08:18:06	00:00	3.74	0	23.978	0	4.959	0
52	17-Nov-2007 08:11:33	00:00	3.74	0	24.264	0	4.946	0
53	03-Dec-2007 07:43:01	-00:00	2.51	0	16.679	0	12.729	0
54	19-Dec-2007 05:01:22	00:00	3.01	0	16.278	0	26.485	0
55	04-Jan-2008 00:43:03	00:00	3.97	0	16.01	0	37.967	0
56	15-Jan-2008 21:54:29	-00:00	3.27	0	11.735	0	47.014	0
57	27-Jan-2008 20:27:55	-00:00	3.27	0	11.88	0	46.983	0
58	08-Feb-2008 19:20:54	00:02	3.26	6	12.314	0	47.57	0
59	20-Feb-2008 19:33:46	-00:01	3.26	0	12.16	0	47.573	-0.001
60	02-Mar-2008 05:09:34	-00:03	3.75	0	10.502	0	56.737	0
61	12-Mar-2008 20:57:06	00:00	3.75	0	10.732	0	56.714	0
62	23-Mar-2008 12:19:16	00:00	3.75	0	10.704	0	56.709	0
63	01-Apr-2008 20:24:20	00:00	4.32	0	9.487	0	63.651	0
64	11-Apr-2008 10:24:52	-00:00	4.32	0	9.664	0	63.623	0
65	20-Apr-2008 23:47:02	00:00	4.32	0	9.477	0	63.643	0
66	30-Apr-2008 12:55:41	00:00	4.31	0	9.576	0	63.633	0
67	10-May-2008 02:14:02	-00:00	4.31	0	9.593	0	63.628	0
68	17-May-2008 23:45:52	-00:00	3.26	0	7.926	0	69.972	0
69	25-May-2008 22:56:44	00:00	3.26	0	8.057	0	69.957	0
70	01-Jun-2008 22:22:42	00:00	2.70	0	7.144	0	75.428	0
71	09-Jun-2008 01:10:11	00:00	2.70	0	7.15	0	75.426	0
72	16-Jun-2008 03:45:53	00:00	2.68	0	7.252	0	75.458	0
73	23-Jun-2008 06:20:32	00:00	2.68	0	7.052	0	75.475	0
74	30-Jun-2008 08:50:27	00:00	2.68	0	7.338	0	75.476	0
75	07-Jul-2008 11:19:06	00:00	2.68	0	7.013	0	75.497	0

ADDITIONAL TRAJECTORY MODIFICATIONS

OTM-038 Location

OTM-038, a near periapsis cleanup maneuver, is located just one day after D1. Since OTM-038 is primarily an energy correction maneuver, the maneuver size is an inverse linear function of the instantaneous spacecraft velocity. This, coupled with the large velocity gradient near periapsis due to the orbit's eccentricity, makes OTM-038 highly sensitive to temporal variations (Fig. 9). Ideally, an approximate 14 hour shift (earlier) in the OTM-038 maneuver time would fully exploit an ~8.5 m/s savings. However, as stipulated in the Cassini Mission Plan, all maneuvers must be executed during a single Deep Space Network (DSN) tracking pass [15]. Furthermore, given a 9-hour OTM pass, all maneuvers are performed 6 hours into the pass, which allows for verification of spacecraft health and safety, approximately two hours of pre-maneuver coherent 2-way Doppler (accounts for 2 hour, 36 minute round trip light time), and redundant uplinks of the maneuver sequence. Nominally, OTM-038 was scheduled to be executed on October 12, 2005 16:45 UTC (DOY 285) centered over Goldstone; Adhering to the aforementioned constraints, the OTM-038 execution time was moved to October 12, 2005 5:57 UTC (DOY 285) over the previous DSN pass (Madrid) resulting in an ~7.5 m/s Δv savings (Fig. 10).

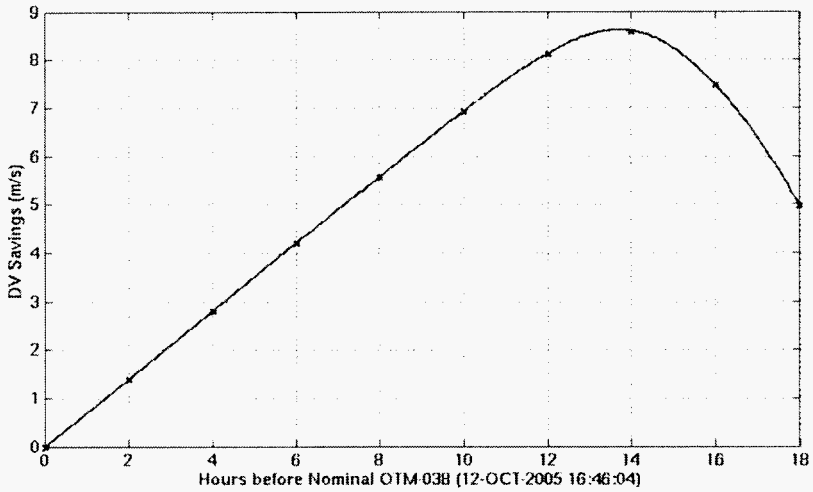

Figure 9: Δv savings associated with OTM-038 timing variations.

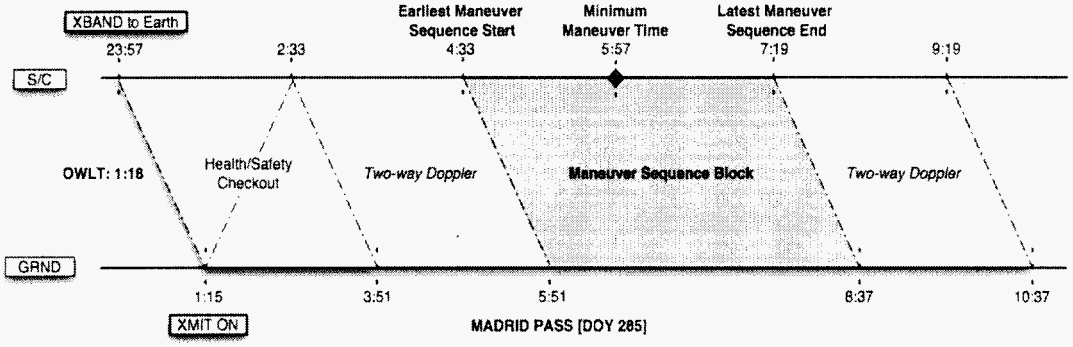

Figure 10: OTM-038 maneuver timeline

Hyperion-1 Tweak

Due to trajectory deviations caused by the Tethys tweak, it became more Δv-efficient to lower the targeted Hyperion flyby (H1) from 1010 km to 510 km[†]. Furthermore, the B-plane angle, nominally set to −152° (EMO2000) [9], was changed to 152°, which will maintain a very similar solar phase profile. Implementing both changes rendered an addition 1.15 m/s savings while simultaneously increasing the H1 science resolution/quality.

APPROVED TRAJECTORY

All analysis provided to the Project for approval was based on a 2000 km 15Te non-targeted flyby; however due to the amount of conservatism inherent to the navigational analysis, in addition to a "the closer the better" scientific community mentality, the Project approved, contingent on an updated covariance analysis verifying the maintenance of H1 pointing requirements, a 1500 km non-targeted 15Te flyby. A trajectory modification specific Δv-cost breakdown is provided in Figure 11. Refer to Ref. 16 for complete quantification (tables and figures) of all relevant quantities and parameters associated with the reference trajectory update.

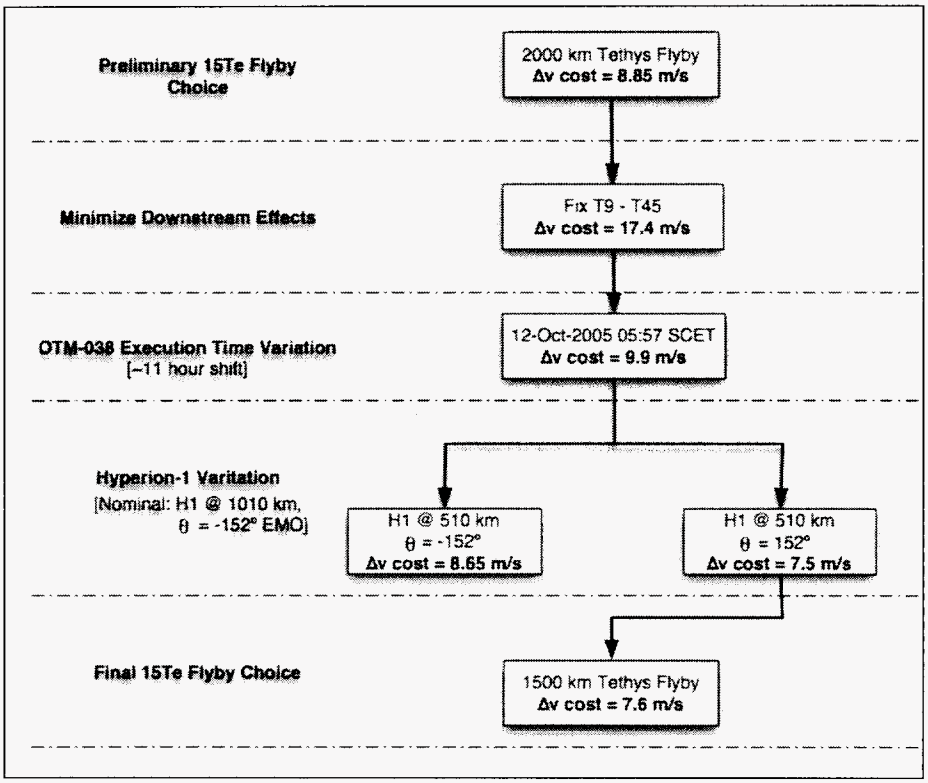

Figure 11: Trajectory option summary and the associated Δv costs.

[†] Additional 10 kilometers was due to ambiguities in software modeling Hyperion as a sphere; in reality Hyperion is a chaotically tumbling ellipsoid of poorly know shape. The 510 km flyby altitude is relative to sphere of radius 130 km.

UPDATED OD COVARIANCE ANALYSIS

The main challenge intrinsic to all covariance analyses thus far in achieving the required H1 pointing uncertainties is the short time (3 days, 15 hours) between the Rev-15 apoapsis maneuver (OTM-033) and approach maneuver (OTM-034). Typically, for a given maneuver, two days are allocated for the maneuver design process. In the case of OTM-034, this strategy would render a data cutoff (DCO) only 39 hours after OTM-033. However, since such rapid OD solution convergence is impossible for the given orbital geometry, the OTM-034 DCO was changed from 2 days to approximately 17 hours prior to OTM-034 [12]. This modification allowed the placement of additional optical navigation images prior to the OTM-034 DCO (in addition to a DSN tracking pass required to download the images), which based on previous covariance studies, will expedite the OD solution convergence, and hence, decrease spacecraft position uncertainties necessary to meet H1 pointing requirements.

Due to the decrease in 15Te flyby altitude, the magnitude of OTM-033 increased; as a result, the OTM-033 deterministic maneuver execution errors will be larger, which translate into a larger statistical OTM-034. Consequently, the updated OTM-034 execution errors will also increase. Lastly, OTM-034 execution errors (mapped to H1) must be scale to account for Saturn periapsis passage (significant gravitational effects magnify OTM-034 errors).

The epoch used for the update covariance analysis was 28-August-2005, which corresponded to the Rev-14 Saturn-relative apoapsis. Figure 12 compares the Navigation Plan and the updated covariance study H1 B-plane uncertainties (EMO2000*, Hyperion-centered) [17]. The peaks in Figure 12 correspond to maneuver execution errors. The main drop in the uncertainties occurs at Titan-7 on 7 September 2005.

Table 6 lists the OTM-034 DCO B-plane uncertainties mapped to H1 for the updated covariance study and the Navigation Plan. While an increase in B-plane and downtrack uncertainties resultant from lowering 15Te, Table 7 confirms the increased uncertainties do not preclude meeting the H1 pointing requirements, hence verifying the navigational capability to fly a 1500 km, non-targeted 15Te flyby.

Table 6: OTM-034 DCO H1 B-Plane uncertainties comparison between the Navigation Plan and the updated covariance analysis.

Flyby	DCO_TIME (days)	MAP_TIME	Semi-major Axis (km)	Semi-minor Axis (km)	Theta (deg)	Downtrack (km)	TCA (sec)
Hyperion-1 (Updated)	-3.485	0.00	12.8	2.6	75	3.1	0.6
Hyperion-1 (Nav Plan)	-3.708	0.00	9.2	3.1	76	2.2	0.4

* Earth Mean Orbital Plane of J2000 coordinate system

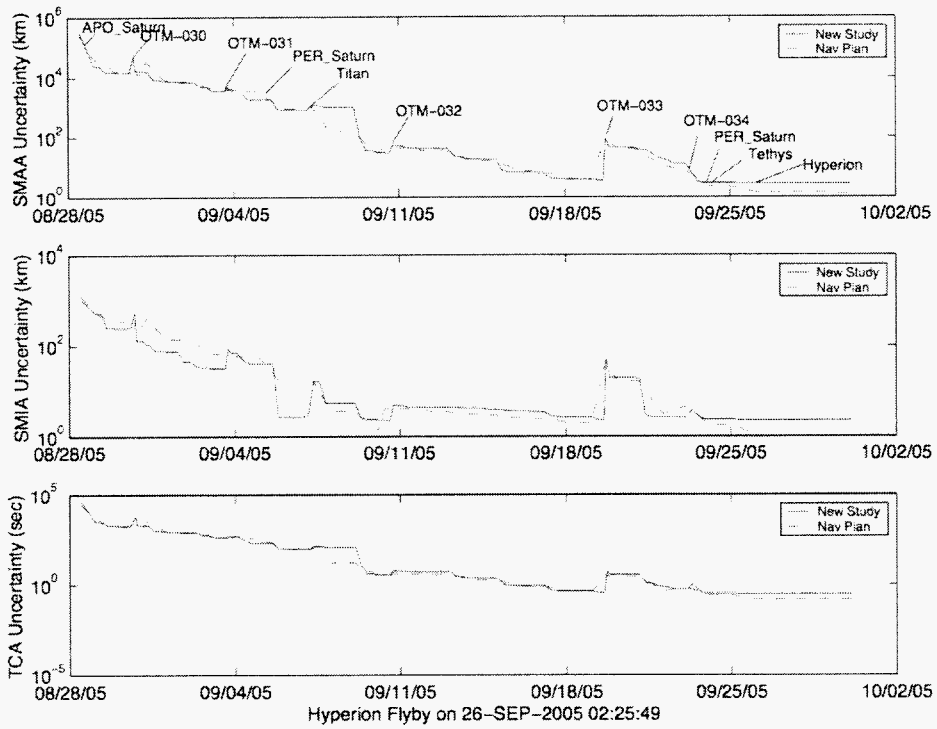

Figure 12: H1 B-Plane and downtrack uncertainties comparison between the Navigation Plan and the updated covariance analysis.

Table 7: Pointing uncertainties comparison between updated covariance analysis and Nav Plan

Flyby Body	Flyby Time (UTC)	Incoming Asymptote Pointing Uncertainty (mrad)		Outgoing Asymptote Pointing Uncertainty (mrad)		Max. Pointing Uncertainties (mrad)
		@20000 (km)	@30000 (km)	@20000 (km)	@30000 (km)	
Tethys (15Te)	24-Sep-2005 02:43:24	0.39	0.26	0.41	0.28	3.64
Hyperion-1 (Updated)	26-Sep-2005 02:25:49	**0.68**	**0.45**	**0.68**	**0.45**	24.57
Hyperion -1 (Nav Plan)	26-Sep-2005 01:42:15	0.46	0.30	0.47	0.31	7.44
Requirement	-	**1.02**	**0.79**	**1.02**	**0.79**	-

CONCLUSION

Through the implementation of various trajectory modifications and constraints, the addition of a 1500 km, non-targeted Tethys flyby (15Te) was successfully added to the 4-year Cassini tour. Localized trajectory deviations minimized spacecraft sequence changes, while the additional required Δv, 7.6 m/s, was smaller than other comparable icy moon Δv averages. Furthermore, the addition of a close Tethys flyby will provide an opportunity to fulfill a major goal of the extended mission (place Tethys in context of other icy satellites) during the prime mission.

APPENDIX A

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "*B*–plane" coordinates [18] (see Fig. A.1). 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*.

Trajectory errors in the B-plane are often characterized by a one–sigma dispersion ellipse, shown in Figure A.1. SMAA and SMIA denote the semi–major and semi–minor axes of the ellipse; θ is the angle measured clockwise from the T axis. 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-infinity vector.

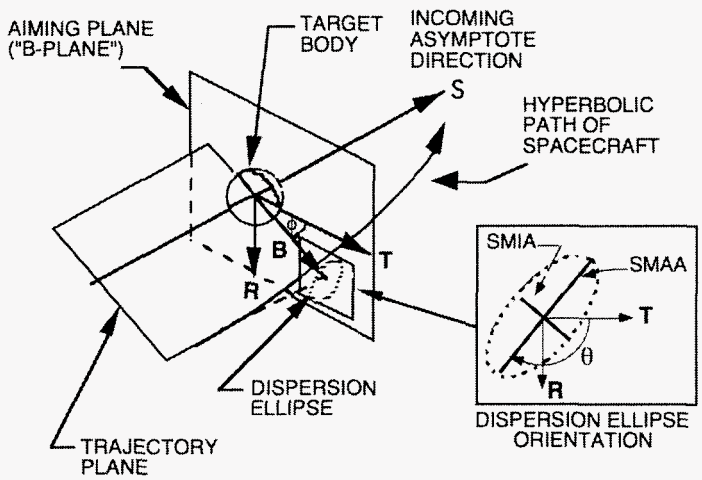

Figure A.1: B-plane Coordinate System

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