AAS 07-000

CASSINI ORBIT DETERMINATION PERFORMANCE DURING SATURN SATELLITE TOUR AUGUST 2005 – JANUARY 2006

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During the period spanning the second Enceladus flyby in July 2005 through the eleventh Titan encounter in January 2006, the Cassini spacecraft was successfully navigated through eight close-targeted satellite encounters. Three of these encounters included the 500 km flybys of the icy satellites Hyperion, Dione and Rhea and five targeted flybys of Saturn's largest moon, Titan. This paper will show how our refinements to Saturn's satellite ephemerides have improved orbit determination predictions. These refinements include the mass estimates of Saturn and its satellites by better than 0.5%. Also, it will be shown how this better orbit determination performance has helped to eliminate several statistical maneuvers that were scheduled to clean-up orbit determination and/or maneuver-execution errors.

INTRODUCTION

The Cassini spacecraft (S/C) has been in orbit around Saturn since June 30, 2004. From June 2004 through July 2005, the orbiter made nine successful close-targeted encounters with three of the major satellites in the Saturnian system: Phoebe, Titan and Enceladus. In January 2005, Cassini released the Huygens probe which was targeted successfully for a descent to the surface of Titan. Antreasian et al., 2005 (Ref. [1]) report the orbit determination (OD) results that supported navigation during this early phase of the Cassini satellite tour. Bordi et al., 2005 (Ref. [2]) discuss the results of the Huygens probe navigation. After the second Enceladus flyby in July 2005 through the eleventh Titan encounter in January 2006, the Cassini S/C has been navigated successfully through nine additional close satellite encounters. Four of these included the closest yet flybys of the icy satellites Hyperion, Tethys, Dione and Rhea. Except for the non-targeted 1500-km altitude Tethys encounter, the targeted flyby altitudes for these icy satellite encounters were approximately 500 km. This period also included five targeted flybys of Saturn's largest moon, Titan, with altitudes ranging from 1075 km to 10,400 km. Table 1 lists the achieved times of closest approach (TCA) and altitudes of the close satellite encounters reported in this paper. Also listed in Table 1 are the hyperbolic approach velocities for each encounter, orbit periods and inclination with respect to Saturn Mean Equator of date after the encounters.

The satellites' ephemeris errors were the major navigation error sources prior to their close encounters with Cassini. Improvements in the satellite ephemerides, Saturn and satellite masses, Saturn zonal harmonics, and Saturn pole vector through the OD process are important for navigating the tour. The OD performance during the first year of the Saturn tour (June 2004 – July 2005) enabled significant improvements in these parameters, as well as the non-gravitational forces affecting the S/C's motion.[1] These improvements in the OD processes along with Cassini's very accurate

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Table 1 Targeted Encounters of the Cassini Saturn Satellite tour, August 2005 - January 2006.

Encounter		Achieved TCA* (ET-SCET)	TCA Error‖ (s)	Achieved Altitude¶ (km)	Altitude Error‖ (km)	In or Out‡	V_∞ (km/s)	Orbit Period† (days)	Inc† (deg)	Rev No.
Titan-6	T6	22-AUG-2005 08:54:42	+0.2	3660.2	-2.3	O	5.61	16.0	15.6	14
Titan-7	T7	7-SEP-2005 08:13:02	-0.02	1074.8	-0.2	O	5.65	18.4	0.3	15
Tethys-1§	Te1	24-SEP-2005 02:43:24	-0.17	1496.9	+12.6	O	9.01	18.1	0.3	16
Hyperion-1	H1	26-SEP-2005 02:25:53	-0.17	487.7	+3.9	O	5.64	18.2	0.3	16
Dione-1	D1	11-OCT-2005 17:53:04	-0.01	499.0	+5.2	I	9.10	18.9	0.4	17
Titan-8	T8	28-OCT-2005 04:16:29	-0.04	1353.0	+0.1	I	5.54	28.5	0.4	18
Rhea-1	R1	26-NOV-2005 22:38:43	-0.41	502.0	+2.0	I	7.29	27.4	0.4	19
Titan-9	T9	26-DEC-2005 19:00:30	-0.002	10,410.94	-0.07	O	5.49	23.4	0.4	20
Titan-10	T10	15-JAN-2006 11:42:31	-0.4	2042.8	-1.1	I	5.48	39.2	0.4	21

* Time of closest approach (TCA) given in ephemeris time (ET) - S/C event time (SCET).

† Conditions after encounter, inclination is wrt Saturn Mean Equator.

‡ Encounter occurs before (inbound) or after (outbound) Saturn periapsis.

§ Non-targeted close encounter.

¶ Altitude not explicitly targeted in maneuver designs.

‖ Altitude and TCA errors are wrt predicted OD in the case of canceled approach maneuver or controlled where the altitude-equivalent B-plane parameters were targeted.

maneuver performance[3] have helped eliminate several planned statistical maneuvers which were scheduled to clean-up OD and/or maneuver-execution errors for the next phase of the tour reported herein. Accurate OD exceeded, in most cases, the predicted instrument pointing requirements to targeted and non-targeted satellites. The required 1-σ accuracies are 1.02 mrad for flyby altitudes of 20,000 – 30,000 km and 0.79 mrad for altitudes greater than 30,000 km. In general, pointing for satellite observations was corrected by either performing an approach maneuver (final targeting maneuver to an encounter) or by updating instrument-pointing vectors based on the latest OD pointing predictions. This paper will show how well the navigation control errors and OD solutions predicted the satellite encounter B-plane flyby conditions and the instrument pointing for observations during the flybys. Also, this paper will explain how the satellite ephemerides have improved and changed over this period. Lastly, this paper will discuss how the satellite masses, which were largely uncertain prior to the satellite tour, have been well determined by the time of the Titan-10 encounter.

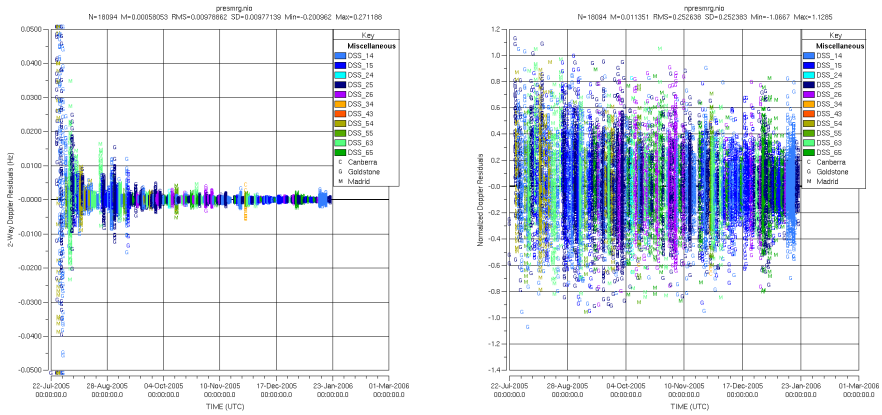
Information on Cassini's navigation for the Saturn satellite tour is given in the Cassini Satellite Tour Navigation Plan (Nav Plan).[4] Details of the OD objectives, strategies, processes, and modeling for Cassini's tour navigation used in this report are explained by Antreasian et al., 2005 (Ref. [1]). Criddle et al., 2006 (Ref. [5]) discuss in detail the OD results during the unique back-to-back Tethys – Hyperion flybys on September 24 – 26, 2005. Pelletier et al., 2006 (Ref. [6]) provide an analysis of the drag modeling for low altitude Titan encounters ($<$ 1200 km) such as was incorporated in the OD processes for the low 1075-km altitude Titan-7 flyby on September 7, 2005.

CASSINI ORBIT DETERMINATION BACKGROUND

Tracking Data

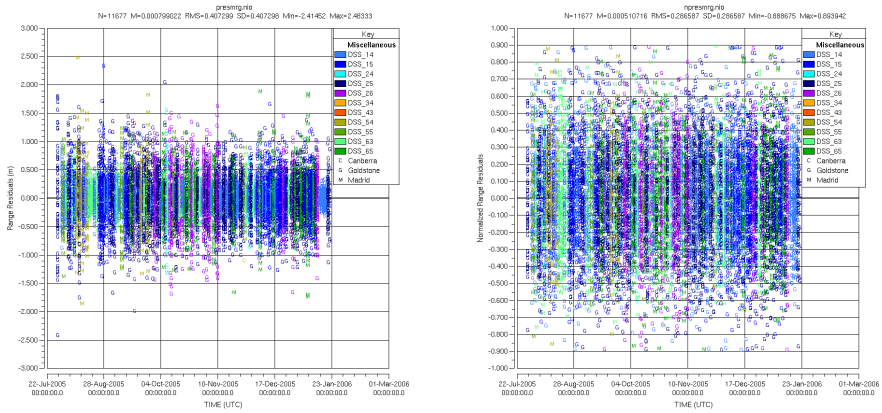
Coherent 2-way X-Band Doppler, range tracking data and telemetry were obtained through the daily use of NASA's Deep Space Network (DSN) in Madrid, Spain and Goldstone, California*.

*Due to the high declination of Saturn, the much shorter view period of Cassini from the southern DSN complex in Canberra, Australia did not provide ample tracking coverage and thus was rarely used.



(a) Actual (b) Normalized

Figure 1 Two-way Doppler residuals from July 22, 2005 through January 21, 2006 (Titan-6 to Titan-10 flyby). Residuals normalized by their weights are shown in (b).



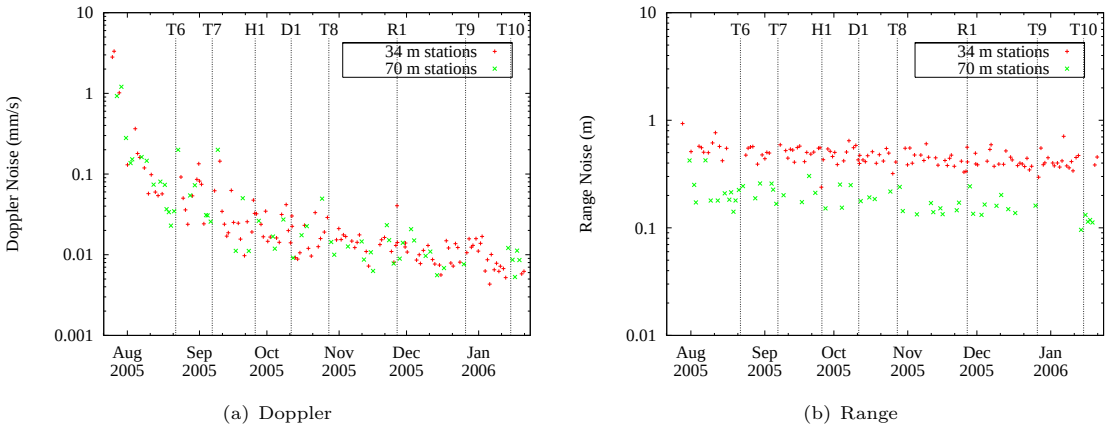
(a) Actual (b) Normalized

Figure 2 Two-way range residuals from July 22, 2005 through January 21, 2006 (Titan-6 to Titan-10 flyby). Residuals normalized by their weights are shown in (b).

Due to the 2.5 – 3 hour round-trip light time of the tracking signal from the station to the S/C at Saturn and back, a nine-hour tracking pass would acquire approximately 6 – 7 hrs. of 2-way radio-metric data. Generally, tracking data were not acquired within twelve hours before and after a targeted encounter due to the science observation geometries precluding the pointing of the High Gain Antenna towards Earth. Two-way and three-way radio-metric data were, however, acquired during the Rhea-1 encounter on November 28, 2005 due to a radio-science experiment for determining Rhea's gravity harmonics. These data were included in the OD solutions to support the Rhea-1 flyby reconstruction and the Titan-9 approach.

The radio-metric data were calibrated to remove the measured variability of the Earth's ionosphere and troposphere effects on the data. Corrections to Earth's polar motion and timing were also applied to the measurement models. Errors due to station locations (2–5 cm), troposphere (1-cm wet, 1-cm dry), ionosphere (5-cm day and 1-cm night), and Earth orientation (2 cm) are all considered in the OD filter. Per-station and per-pass ranging biases are estimated with *a priori* uncertainties of one meter and three meters, respectively.

The Doppler and range data were weighted on a per-pass basis using the data noise standard

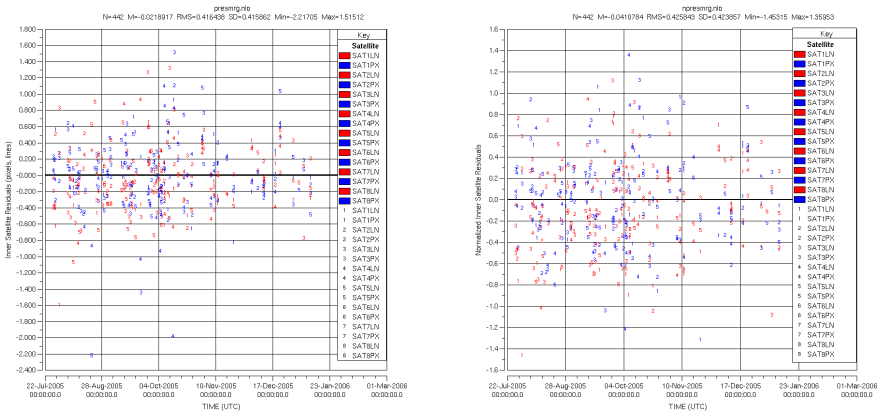


(a) Doppler (b) Range

Figure 3 Radio-metric data noise: 2-way Doppler in (a) & range in (b) from July 22, 2005 through January 21, 2006 (Titan-6 to Titan-10 flyby).

deviation of tracking pass multiplied by a scale factor of 3.36 to compensate for diurnal solar plasma noise effects on the data. The post-fit residuals of the 2-way Doppler data used in the OD solutions during the orbits spanning the Titan-6 – Titan-10 encounters (July 22, 2005 – January 22, 2006) are shown in Figure 1.a. Figure 2.a shows the corresponding range residuals. These data normalized by their weights are shown, respectively for the 2-way Doppler and range, in Figures 1.b and 2.b. During the beginning of this period the data noise was dominated by solar plasma effects during the solar conjunction (July 14 – August 3, 2005) when the radio signal to and from Cassini passed close to the sun. The Sun-Earth-Probe (SEP) angle for Cassini was below 7 deg during this time. Pass-to-pass data noise was generally better than 0.1 mm/s (for 60-second count time) for 2-way Doppler data and 1 m for the range data as shown in Figure 3. The better signal-to-noise capabilities of DSN's 70-meter antennas than the smaller 34-meter dishes is evident in the better range noise, as exhibited in Figure 3.b. During the solar conjunction period, the Doppler data were de-weighted and the range data were subject to deletion especially for SEP angles of 5 deg or less. For most of the tour, the Doppler data had been compressed with 5-minute count times. Data acquired before and after maneuver executions were compressed to a more frequent count time of 60 s. No tracking data were acquired during Orbit Trim Maneuvers (OTMs) and occasional small ΔV events when the spacecraft was not pointed toward Earth.[1]

Optical navigation (opnav) images of any of the nine satellites, listed in Figures 4 and 5, were shuttered by Cassini's narrow angle camera which has a 6 mrad field of view and a 2000 mm focal length. The opnav schedule was reduced during the end of this tour phase (after November 2005) from three to six opnav images shuttered per day to approximately three to six images every 3 days. The opnavs residuals are shown for the inner satellites in Figure 4 and for the outer satellites in Figure 5; both the actual data and the data normalized by their weights are shown. Corrections to the camera pointing (rotation angles about the pixel, line axes and camera boresight) based on the stars were estimated in the OD filter for each image with an *a priori* uncertainty of 1 deg for each axis using a white noise stochastic model. These corrections were usually much less than 1μrad in the angles about the pixel and line axes and less than 0.5 mrad for the *twist* angle about the boresight. Zeroth and first order phase biases were estimated for all the Titan opnavs with an *a priori* uncertainty of 5%. The opnav data were weighted based on the resolution of the images taken at different ranges from the satellites multiplied by a satellite dependent scale factor (see Ref. [1]). Stars were weighted at the larger of 0.1 pixels or their formal point-source sigma.



(a) Actual

(b) Normalized

Figure 4 Inner Satellite Optical Residuals (July 22, 2005 – January 21, 2006). Residuals normalized by their weights are shown in (b). Symbols: 1 = Mimas, 2 = Enceladus, 3 = Tethys, 4 = Dione, 5 = Rhea.

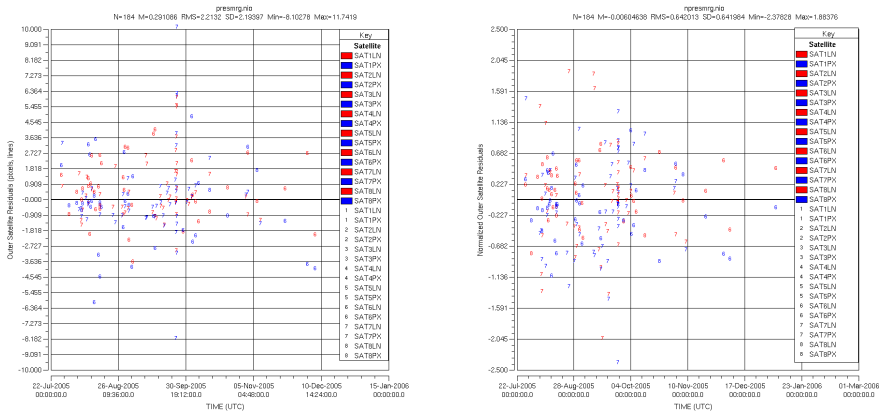
OD Filter Strategy

The OD operational data arc to support a targeted encounter begins near Saturn apoapsis one and a half orbital revolutions prior to the flyby. The data arc generally cannot extend beyond two satellite encounters for reasons explained by Antreasian et al., 2005 (Ref. [1]) For each data arc, the S/C initial state at epoch was estimated as Cartesian position and velocity in a Saturn-centered Earth-Mean-Equator and Equinox of 2000 (EME2000) frame. The *a priori* values were taken from a previous data arc OD solution with the data cut off set to the epoch of the current arc. The *a priori* state covariance matrix from this solution was mapped to the current epoch and was scaled by a factor of five.

The estimated satellite parameters (satellite states, masses, Saturn, Saturn pole, $J2, J4$, and system mass) from the prior arc solution were used to establish an updated satellite model. The post-fit correlated covariance of these satellite-Saturn parameters were then used as the current arc's *a priori* satellite covariance. The filter parameters included the estimation of the initial position and velocity of the nine satellites, Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus and Phoebe at the satellite ephemeris epoch of January 2, 2004. To speed up the integration of the satellite ephemeris, this epoch was changed to July 31, 2005 for arcs starting after the Dione-1 flyby on October 11, 2005. The trajectory of Saturn was estimated via the Set III parameters; and the satellite and Saturn-Barycenter masses, Saturn J2 and J4, and the Saturn pole orientation were also estimated.

At 9.5 A.U., thermal radiation pressure from Cassini's onboard power supply is one magnitude greater than solar pressure. This force was modeled as an exponential decay model with an estimated scale parameter in each of the S/C axes with an *a priori* uncertainty equal to 10% of the nominal. The force due to solar pressure was included in the S/C orbit integration with nominal reflectivity values, but no parameters were estimated.

During each data arc four to five OTMs were generally scheduled using either the S/C main engine for large burns (> 0.3 m/s) or Reaction Control System (RCS) thrusters for smaller burns (< 0.3 m/s). For each maneuver, the magnitude, direction and start time of the maneuver were estimated using an *a priori* uncertainty based on the Gates execution-error model which accounts for fixed and proportional errors.[3,7] The reconstructions of these maneuvers based on the orbit determination included in this paper are reported by Wagner et al., 2006 (Ref. [7]) RCS thrusting due to the Reaction Wheel Assembly (RWA) biasing, spin downs, attitude turns, attitude control on the RCS system (deadbanding) were modeled as impulsive maneuvers (small ΔV events) and



(a) Actual (b) Normalized

Figure 5 Outer Satellite Optical Residuals (July 22, 2005 – January 21, 2006). Residuals normalized by their weights are shown in (b). Symbols: 6 = Titan, 7 = Hyperion, 8 = Iapetus, 9 = Phoebe.

the ΔV magnitudes were estimated. Table 2 lists small ΔV events that occurred during this time frame.

Unmodeled small forces acting on the S/C such as solar pressure mis-modeling were accounted for using a set of stochastic accelerations with scale parameters estimated in S/C-fixed axes. These were modeled as white noise with spherical *a priori* uncertainty of 0.5×10^{-12} km-s^{-2} and batches every 8 hours. Nominally, the S/C was under RWA attitude control where the S/C does not experience random thruster firings. However, attitude control occasionally is maintained with RCS, usually during satellite encounters. This is done in order to achieve faster turning rates and greater control authority to compensate for drag torques during low Titan atmospheric passes such as during the 1075-km altitude Titan-7 flyby. The thrusting activity during these flybys was predicted using either discrete-impulsive small ΔV events or a discontinuous acceleration model. After the encounters, RCS ΔV telemetry replaced the prediction model, the stochastic accelerations were changed so that the *a priori* uncertainty was increased a few orders of magnitude higher, and the batch time reduced to 5 min. We found it to be very challenging to accurately model and estimate the forces of the thruster activity during these flybys, especially since tracking data could not be collected during these activities and since imprecise modeling/estimation of these activities had the potential of degrading the satellite ephemeris or S/C orbit prediction for the next encounter.

TARGETED ENCOUNTER RESULTS

As previously mentioned, during the period between August 2005 and January 2006, Cassini performed eight targeted encounters and one non-targeted encounter of Saturn's major moons as listed in Table 1. Between each encounter, a three maneuver strategy was generally employed [7] . The first maneuver, called the clean-up maneuver, occurred approximately three days after an encounter. Typically, it was optimally chained with the second maneuver, which occurs near apoapsis, to target the following encounter. This maneuver chain spans several encounters, keeping downstream ΔV costs down while controlling approach asymptote errors. The third maneuver, referred to as the approach maneuver, was a statistical maneuver that took place generally about three days prior to an encounter to clean up any OD and/or maneuver errors. Table 3 lists the major events from Titan-6 (T6) through Titan-10 (T10) including all targeted encounters, Saturn periapses, maneuvers, maneuver data cutoffs (DCOs), and data arc start and end times. Figures 6 and 7 display the Cassini orbits that encompass the encounters, the location of the maneuvers, and the data-arc epochs described below. Table 1 lists the errors of the TCA and altitudes of these close satellite

Table 2 Small RCS ΔV Events

Event	Event Midpoint SCET-UTC	Predict (mm/s)		Estimate (mm/s)		Direction	RA (deg)	Dec (deg)	Error (mm/s)
RWA end of sequence bias	31-JUL-2005 19:32:00.0	3.218	± 5.000	3.640	± 0.051	EARTH	-55.79	-20.01	0.422
RWA spin down before OTM-26	03-AUG-2005 11:18:20.8	0.463	± 5.000	0.808	± 0.188	EARTH	-55.38	-19.95	0.345
RWA spin up after OTM-26	03-AUG-2005 12:12:20.8	8.512	± 5.000	6.643	± 0.342	EARTH	-55.38	-19.95	-1.869
RWA spin down before OTM-27	10-AUG-2005 12:50:55.6	8.546	± 5.000	8.534	± 0.080	EARTH	-54.39	-19.75	-0.011
RWA spin up after OTM-27	10-AUG-2005 13:42:02.1	2.743	± 5.000	2.486	± 0.098	EARTH	-54.38	-19.75	-0.257
RWA bias	18-AUG-2005 12:11:38.4	1.724	± 5.000	1.695	± 0.018	EARTH	-53.44	-19.57	-0.030
RWA spin down before OTM-29	25-AUG-2005 16:36:34.6	2.519	± 5.000	2.915	± 0.049	EARTH	-52.46	-19.34	0.396
RWA spin up after OTM-29	25-AUG-2005 17:30:30.1	7.551	± 5.000	6.703	± 0.102	EARTH	-52.46	-19.34	-0.847
RWA spin down before OTM-30	30-AUG-2005 18:12:41.1	7.384	± 5.000	7.272	± 0.073	EARTH	-51.85	-19.20	-0.112
RWA spin up after OTM-30	30-AUG-2005 19:04:53.5	6.327	± 5.000	7.871	± 0.143	EARTH	-51.84	-19.20	1.544
RWA Friction Test	01-SEP-2005 13:46:00.0	28.851	± 5.000	27.278	± 0.040	EARTH	-51.62	-19.18	-1.573
RWA bias after OTM-31	03-SEP-2005 18:32:08.0	1.280	± 5.000	1.659	± 0.017	EARTH	-51.44	-19.13	0.378
RWA spin down before T-7	07-SEP-2005 07:25:00.5	5.500	± 1.000	5.241	± 0.953	OTHER	-96.01	-13.46	-0.259
RWA spin up after T-7	07-SEP-2005 09:40:00.5	6.920	± 1.000	16.901	± 1.473	OTHER	81.87	19.94	9.981
RWA bias instead of OTM-32	10-SEP-2005 17:59:32.8	7.900	± 5.000	6.667	± 0.918	EARTH	-50.54	-18.90	-1.233
RWA spin down before OTM-33	19-SEP-2005 16:08:50.9	8.559	± 5.000	7.091	± 0.035	EARTH	-49.64	-18.71	-1.468
RWA spin up after OTM-33	19-SEP-2005 17:05:22.8	3.337	± 5.000	4.004	± 0.058	EARTH	-49.64	-18.71	0.667
RWA bias instead of OTM-34	23-SEP-2005 08:58:35.7	2.648	± 5.000	2.802	± 0.012	EARTH	-49.37	-18.60	0.155
RWA bias between Tethys & H1	25-SEP-2005 06:20:39.6	13.331	± 5.000	11.774	± 0.031	EARTH	-49.13	-18.52	-1.557
RWA bias after OTM-35	28-SEP-2005 17:17:45.1	15.776	± 5.000	13.155	± 0.020	EARTH	-48.77	-18.53	-2.621
RWA bias instead of OTM-36	01-OCT-2005 15:06:02.0	15.468	± 5.000	12.946	± 0.010	EARTH	-48.49	-18.48	-2.522
RWA bias instead of OTM-37	08-OCT-2005 10:50:03.0	10.923	± 5.000	11.495	± 0.015	EARTH	-47.96	-18.35	0.572
RWA spin down before OTM-38	12-OCT-2005 05:30:05.9	9.050	± 5.000	7.806	± 0.058	EARTH	-47.73	-18.23	-1.243
RWA spin up after OTM-38	12-OCT-2005 06:16:23.3	1.243	± 5.000	2.260	± 0.056	EARTH	-47.72	-18.22	1.017
RWA bias after OTM-38	21-OCT-2005 16:01:30.5	13.660	± 5.000	10.643	± 0.202	EARTH	-47.03	-18.14	-3.017
RWA spin down before T8	28-OCT-2005 02:42:49.8	10.548	± 1.000	10.574	± 0.999	OTHER	110.43	-1.74	0.026
RCS attitude control during T8	28-OCT-2005 03:54:18.6	9.519	± 5.000	8.830	± 4.908	OTHER	88.54	-7.24	-0.689
RCS attitude control during T8	28-OCT-2005 04:34:10.5	16.167	± 5.000	14.988	± 4.834	OTHER	-35.07	-5.96	-1.179
RWA spin up after T8	28-OCT-2005 05:47:41.3	1.432	± 1.000	1.450	± 0.999	OTHER	-63.43	1.60	0.018
RWA bias	29-OCT-2005 06:16:43.5	6.574	± 5.000	5.124	± 0.012	EARTH	-46.75	-18.02	-1.450
RWA spin down before OTM-41	31-OCT-2005 13:29:17.9	2.218	± 5.000	2.572	± 0.022	EARTH	-46.59	-17.97	0.355
RWA spin up after OTM-41	31-OCT-2005 14:54:33.9	1.595	± 5.000	1.770	± 0.038	EARTH	-46.58	-17.97	0.175
RWA anomaly	04-NOV-2005 16:43:00.0	2.257	± 5.000	2.612	± 0.033	EARTH	-46.40	-17.97	0.355
RWA anomaly	04-NOV-2005 17:06:00.0	2.907	± 5.000	3.113	± 0.036	EARTH	-46.40	-17.97	0.206
RWA bias	10-NOV-2005 14:16:01.0	8.117	± 5.000	6.684	± 0.009	EARTH	-46.12	-17.90	-1.433
RWA spin down before OTM-42	13-NOV-2005 13:39:57.4	4.559	± 5.000	5.128	± 0.017	EARTH	-46.09	-17.92	0.569
RWA spin up after OTM-42	13-NOV-2005 14:42:26.3	2.540	± 5.000	2.699	± 0.021	EARTH	-46.09	-17.92	0.159
RWA bias after OTM-43	23-NOV-2005 14:04:52.2	8.126	± 5.000	9.900	± 0.014	EARTH	-46.11	-17.96	1.774
RWA bias after OTM-44	28-NOV-2005 05:18:12.6	5.206	± 5.000	5.098	± 0.011	EARTH	-46.21	-17.95	-0.108
RWA bias instead of OTM-45	11-DEC-2005 12:23:18.4	3.992	± 5.000	3.052	± 0.008	EARTH	-46.37	-18.04	-0.940
RWA end of sequence bias	17-DEC-2005 11:27:47.9	3.626	± 5.000	4.068	± 0.008	EARTH	-46.63	-18.18	0.442
RWA bias after OTM-47	30-DEC-2005 03:53:05.1	1.357	± 5.000	1.779	± 0.012	EARTH	-47.35	-18.37	0.422
RWA bias instead of OTM-49	12-JAN-2006 10:35:41.7	3.403	± 5.000	3.920	± 0.008	EARTH	-48.28	-18.68	0.517
RWA bias instead of OTM-50	18-JAN-2006 09:52:18.2	6.237	± 5.000	5.677	± 0.008	EARTH	-48.81	-18.73	-0.559

encounters with respect to the predicted altitudes based on either the last OD solution in support of a canceled approach maneuver or the navigation controlled altitude where the altitude-equivalent B-plane parameters are targeted. Table 4 summarizes information on the encounters including 3-dimensional (3-D) B-plane errors[1] (with respect to either the OD predicted or navigation controlled targets) which are quoted in the following encounter descriptions.

Titan-6 (T6)

After the Enceladus-2 encounter (E2) on July 14, 2005, which was reported by Antreasian et al., 2005 (Ref. [1]), Cassini completed one 'empty' orbital revolution around Saturn before embarking towards the seventh Titan encounter (referred to as Titan-6 or T6). The solar conjunction period began as the S/C approached E2. The SEP angle decreased from 7° at E2 to nearly zero on July 24, 2005. Because of the tracking data degradation caused by the solar conjunction, the clean-up maneuver after E2, OTM-26, was planned for 20 days after E2 near periapsis, following Cassini's empty orbit of Saturn. The SEP angle was close to 9° at the time of OTM-26 so the radio-metric data used to determine OTM-26 were not grossly corrupted by the solar plasma. OTM-26, (ΔV = 2.6 m/s) performed on August 3, 2005, was designed together with OTM-27 (2.4 m/s), performed on August 10, 2005, to target the T6 encounter, which occurred on August 22, 2005 at 08:54:42 ET. The OTM-27 burn proved difficult to estimate until the spacecraft neared periapsis just prior to the outbound T6 flyby. The approach maneuver, OTM-28, was canceled since the OD solution delivered six days prior to T6 indicated that the T6 flyby requirements were already being met. Figure 8.a. compares the post-flyby reconstructed solution to both the OTM-27 delivery (target and dispersion) and the OD delivery for the design of OTM-26 in the T6 B-plane. The B-plane T-axis lies in the Earth-Mean-Orbit (EMO) plane. The error between the reconstruction and the navigation control point (OTM-27 delivery) was 14.6 km (including 0.9 s in time of flight) in the B-plane. This error yields a 3-D B-plane error of 0.41-σ. The error between the reconstruction and the OD delivery for

Table 3 Significant Events

Events	Date, Time (UTC)		Events	Date, Time (UTC)	
Solar Conjunction ($-3^o < SEP < 3^o$)	July 21–27, 2005		Saturn Periapsis	October 12, 2005	01:32
Start of T6 Data Arc	July 24, 2005	12:00	Clean-up Burn OTM-38	October 12, 2005	05:58
DCO for OTM-26	August 1, 2005	13:25	End of D1 Data Arc	October 12, 2005	16:00
Saturn Periapsis	August 2, 2005	05:50	DCO for OTM-39	October 19, 2005	11:40
Post Periapsis Deterministic Burn OTM-26	August 3, 2005	11:51	Start of R1 Data Arc	October 20, 2005	06:00
DCO for OTM-27	August 8, 2005	23:25	Apoapsis Burn OTM-39	October 21, 2005	14:59
Apoapsis Burn OTM-27	August 10, 2005	13:22	DCO for OTM-40	October 24, 2005	16:55
Start of T7 Data Arc	August 13, 2005	00:00	Approach Burn OTM-40 - Canceled	October 25, 2005	07:14
DCO for OTM-28	August 16, 2005	17:00	Titan-8 Flyby	October 28, 2005	04:16
Approach Burn OTM-28 - Canceled	August 18, 2005	11:00	Saturn Periapsis	October 29, 2005	22:57
Saturn Periapsis	August 20, 2005	11:17	DCO for OTM-41	October 30, 2005	18:25
Titan-6 Flyby	August 22, 2005	08:54	End of T8 Data Arc	October 31, 2005	12:00
DCO for OTM-29	August 24, 2005	22:40	Clean-up Burn OTM-41	October 31, 2005	13:59
End of T6 Data Arc	August 25, 2005	00:00	DCO for OTM-42	November 10, 2005	18:10
Clean-up Burn OTM-29	August 25, 2005	17:09	Apoapsis Burn OTM-42	November 13, 2005	14:02
DCO for OTM-30	August 28, 2005	22:25	Start of T9 Data Arc	November 16, 2005	06:00
Apoapsis Burn OTM-30	August 30, 2005	18:44	DCO for OTM-43	November 22, 2005	16:55
RWA Friction Test	September 1, 2005	13:45	Approach Burn OTM-43	November 23, 2005	13:03
Start of H1 Data Arc	September 2, 2005	00:00	Rhea-1 Flyby	November 26, 2005	22:38
DCO for OTM-31	September 2, 2005	21:20	DCO for OTM-44	November 27, 2005	08:55
Approach Burn OTM-31	September 3, 2005	17:31	Saturn Periapsis	November 27, 2005	11:22
Saturn Periapsis	September 5, 2005	11:53	End of R1 Data Arc	November 28, 2005	03:00
Titan-7 Flyby	September 7, 2005	08:13	OTM-44	November 28, 2005	04:16
Clean-up Burn OTM-32 - Canceled	September 10, 2005	17:10	DCO for OTM-45	December 8, 2005	15:55
End of T7 Data Arc	September 12, 2005	00:00	Apoapsis Burn OTM-45 - Canceled	December 11, 2005	11:35
Start of D1 Data Arc	September 14, 2005	04:00	Start of T10 Data Arc	December 14, 2005	06:00
DCO for OTM-33	September 15, 2005	21:10	DCO for OTM-46	December 19, 2005	15:25
Apoapsis Burn OTM-33	September 19, 2005	16:41	Approach Burn OTM-46 - Canceled	December 24, 2005	12:25
DCO for OTM-34	September 22, 2005	17:30	Saturn Periapsis	December 24, 2005	21:24
Approach Burn OTM-34 - Canceled	September 23, 2005	07:41	Titan-9 Flyby	December 26, 2005	19:00
Saturn Periapsis	September 23, 2005	21:36	DCO for OTM-47	December 28, 2005	14:15
Tethys-1 Flyby (1500 km altitude)	September 24, 2005	02:43	End of T9 Data Arc	December 30, 2005	01:00
Hyperion-1 Flyby (500 km altitude)	September 26, 2005	02:26	Clean-up Burn OTM-47	December 30, 2005	02:38
DCO for OTM-35	September 26, 2005	20:35	Apoapsis Burn OTM-48 - Deleted	January 3, 2006	02:23
End of H1 Data Arc	September 28, 2005	00:00	DCO for OTM-49	January 9, 2006	13:55
Clean-up Burn OTM-35	September 28 2005	16:11	Approach Burn OTM-49 - Canceled	January 12, 2006	09:23
Apoapsis Burn OTM-36 - Canceled	October 1, 2005	14:26	Titan-10 Flyby	January 15, 2006	11:43
Start of T8 Data Arc	October 2, 2005	12:00	Saturn Periapsis	January 17, 2006	06:59
DCO for OTM-37	October 6, 2005	19:50	DCO for OTM-50	January 17, 2006	13:39
Approach Burn OTM-37 - Canceled	October 8, 2005	05:57	Clean-up Burn OTM-50 - Canceled	January 18, 2006	08:37
DCO for OTM-38	October 10, 2005	18:55	End of T10 Data Arc	January 21, 2006	07:30
Dione-1 Flyby	October 11, 2005	04:41			

OTM-28 design was 3.6 km (0.2 s in time of flight) in the B-plane. This error yielded a 3-D error of 0.96-σ. The achieved altitude was approximately 3660.2 km.

Titan-7 (T7)

The attitude for the science turns during the T6 encounter was controlled by the RWA system so no thrusting events took place. Following the T6 flyby, two tracking passes were incorporated into the OD filter to design the clean-up maneuver, OTM-29. The main-engine OTM-29 maneuver was executed with a ΔV of 1.5 m/s on August 25, 2005. The fairly sizable 14.4 m/s deterministic apoapsis maneuver, OTM-30, occurred on August 30, 2005, also using the main engine. Since the period of the orbit from T6 to Titan-7 (T7) was only 16 days, there was not much time between maneuvers to converge the OD before designing the next OTM. A special RWA friction test[1] consisting of several RCS thrusting events, took place on September 1. The total accumulated ΔV was 27.28 $\pm$ 0.04 mm/s along the Earth-line direction. The nature of the test did not allow for an accurate predictive model, so this event took place prior to the final DCO for the approach maneuver (OTM-31) which was executed approximately four days before T7 with a ΔV of 65 mm/s. All maneuvers performed well within 1-σ.[7] The T7 encounter occurred on September 7, 2005 08:13:02 ET. The OTM-31 delivery and the reconstructed B-plane are compared in Figure 8.b. As shown in this figure, the error between the reconstruction and the OTM-31 delivery was only 0.146 km and 0.024 s in the B-plane. This error yielded a 3-D error of 0.190 km or 0.18-σ making T7 our best navigated encounter to date.

Hyperion-1 (H1) and Tethys (Te1)

The irregularly shaped moon, Hyperion, orbits just beyond Titan's orbit at a distance of 24.6 Saturn radii (R_s) from Saturn. The moon's tri-axial dimensions are roughly 360 km x 280 km x 225 km. The Hyperion-1 flyby (H1) was redesigned several months prior to the execution of the orbit leading

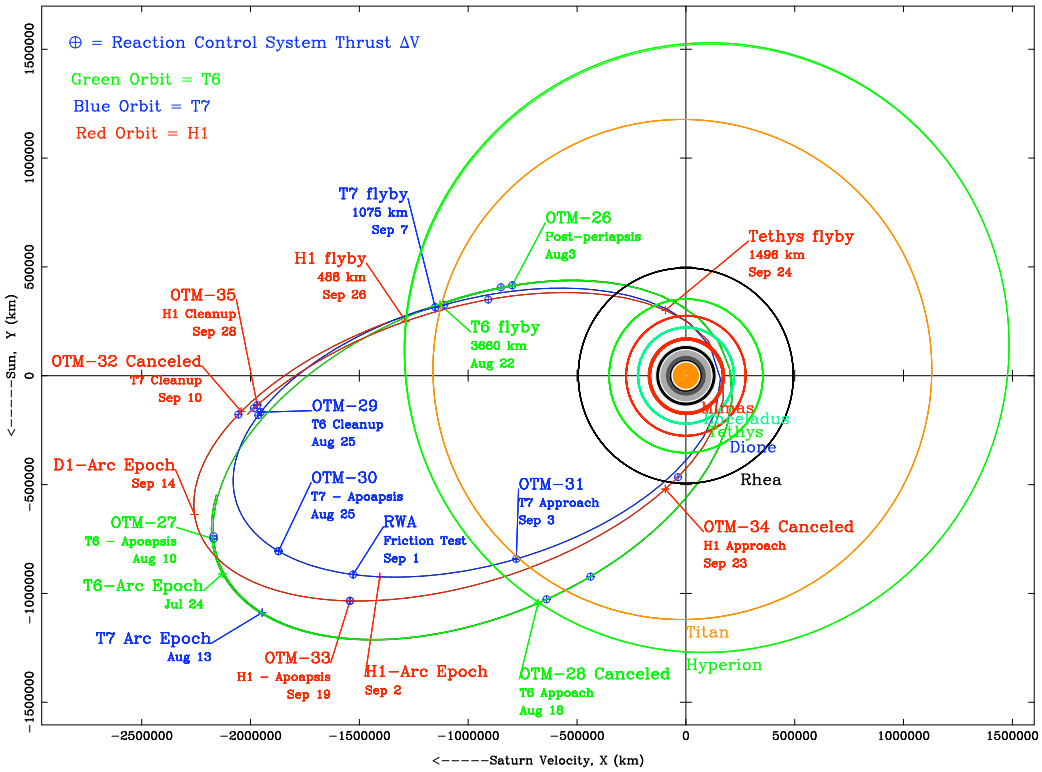


Figure 6 Orbit plot (Saturn North Pole View) from July 22, 2005 – September 26, 2005 encompassing the T6, T7, H1 and Te1 encounters. The green, blue, and red orbits and labels correspond, respectively, to the T6, T7 and H1 approach orbits.

up to its encounter. The new design incorporated a unique close 1500-km non-targeted flyby of Tethys two days before the September 26, 2005 Hyperion flyby. The Hyperion target flyby altitude also was lowered to 510 km from the original 1010 km.[5, 8] This would be the only chance in the prime mission to achieve close-up observations of Tethys. The diameter of Tethys is approximately 1050 km and Tethys orbits at 4.9 R_s from Saturn (third major moon out from Saturn).

At 1075 km, the T7 flyby was the lowest Titan encounter thus far. Apart from RCS activity for science observation turns, the RCS system also compensated for drag torques as the S/C traveled through Titan's upper atmosphere. These thrusting events were modeled with an acceleration profile from the telemetry data. An impulsive ΔV equivalent to the atmospheric drag force at an altitude of 1075 km was estimated at the time of closest approach opposite to the S/C velocity direction. Additional studies where the atmospheric drag coefficient was estimated in lieu of an impulsive ΔV showed good agreement, supporting the current atmospheric model.[6] The magnitude of this drag ΔV was approximately 15.53 mm/s. The accurate modeling of the RCS thrusting and drag force during T7 helped the targeting of the next encounter. Because the T7 flyby was so accurate, the designed ΔV for the +3 day clean-up maneuver, OTM-32, was very small and the Cassini project determined that the designed ΔV for OTM-32 could be absorbed into the OTM-33 apoapsis maneuver with minimal cost. Thus, the OTM-32 burn was canceled. The large deterministic maneuver, OTM-33, (ΔV = 27.9 m/s) was executed on September 19, 2005. Since it would be executed before the Tethys flyby, the design of the final Hyperion targeting maneuver (OTM-34) presented a challenge; the pointing requirements for H1 required tracking data to be included in the OD delivery up to 17 hours before the maneuver execution. However, this approach maneuver was canceled and instead the OD delivered for OTM-34 design was used to update the instrument pointing vectors for science observations of Hyperion. Figure 8.c compares how close the reconstructed trajectory matches the

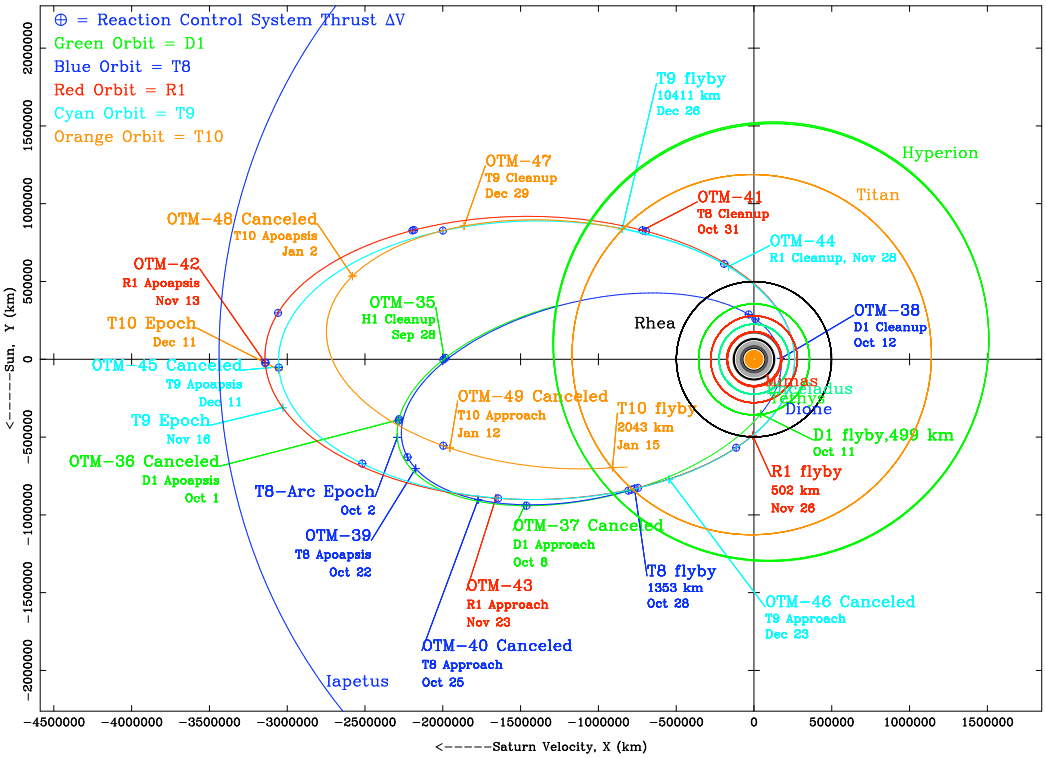


Figure 7 Orbit plot (Saturn North Pole View) from Septeber 26, 2005 – January 22, 2006 encompassing the D1, T8, R1, T9 and T10 encounters. The green, blue, red, cyan and orange orbits and labels correspond, respectively, to the D1, T8, R1, T9 and T10 approach orbits.

predicted aim-point and dispersion of OTM-33 as well as the prediction of the OTM-34 OD delivery at the non-targeted Tethys encounter on September 24, 2005. The achieved altitude was 1497 km, 12.4 km higher than planned. After the flyby, it was determined that the Tethys ephemeris was in error by 18 km in the down-track direction which was approximately 3-σ (from the formal statistics). This error contributed to the small 3-D miss of 5 km or 2-σ in the Hyperion B-plane shown in Figure 8.d from the OTM-34 OD delivery prediction and dispersion.[5] The time of closest approach for H1 was September 26, 2005 02:25:53 ET. The reconstruction was only 0.6-σ (31 km) from the last control point of OTM-33. The Hyperion satellite ephemeris changed very little (< 2 km) after the flyby. The achieved flyby altitude was approximately 487.7 km. This flyby also confirmed the mass that had been estimated indirectly from Hyperion's interaction with Titan. More information on Hyperion's mass determination can be found in Ref. [1] and Ref. [5] .

Dione-1 (D1)

After the H1 encounter, the S/C was placed on course for the next icy satellite, Dione. The diameter of Dione is approximately 1118 km; it orbits Saturn at a distance of 6.3 R_s and its orbital period is 2.7 days. The Dione-1 (D1) encounter occurred on October 11, 2005 17:53:04 ET and was targeted by the post-H1 clean-up maneuver, OTM-35 (0.29 m/s), which took place on September 28, 2005. The OTM-35 delivery B-plane and the reconstructed B-plane values are shown in Figure 8.e. The OTM-35 delivery ellipse included the combination of OD and maneuver execution errors. The factors contributing to the relatively large 16.5 km (2.5-σ) error in the reconstruction compared to the OTM-35 delivery were: errors in the OTM-35 execution, larger than usual errors in RCS event predictions, and errors in Dione's position predicted from the pre-encounter satellite ephemeris. All

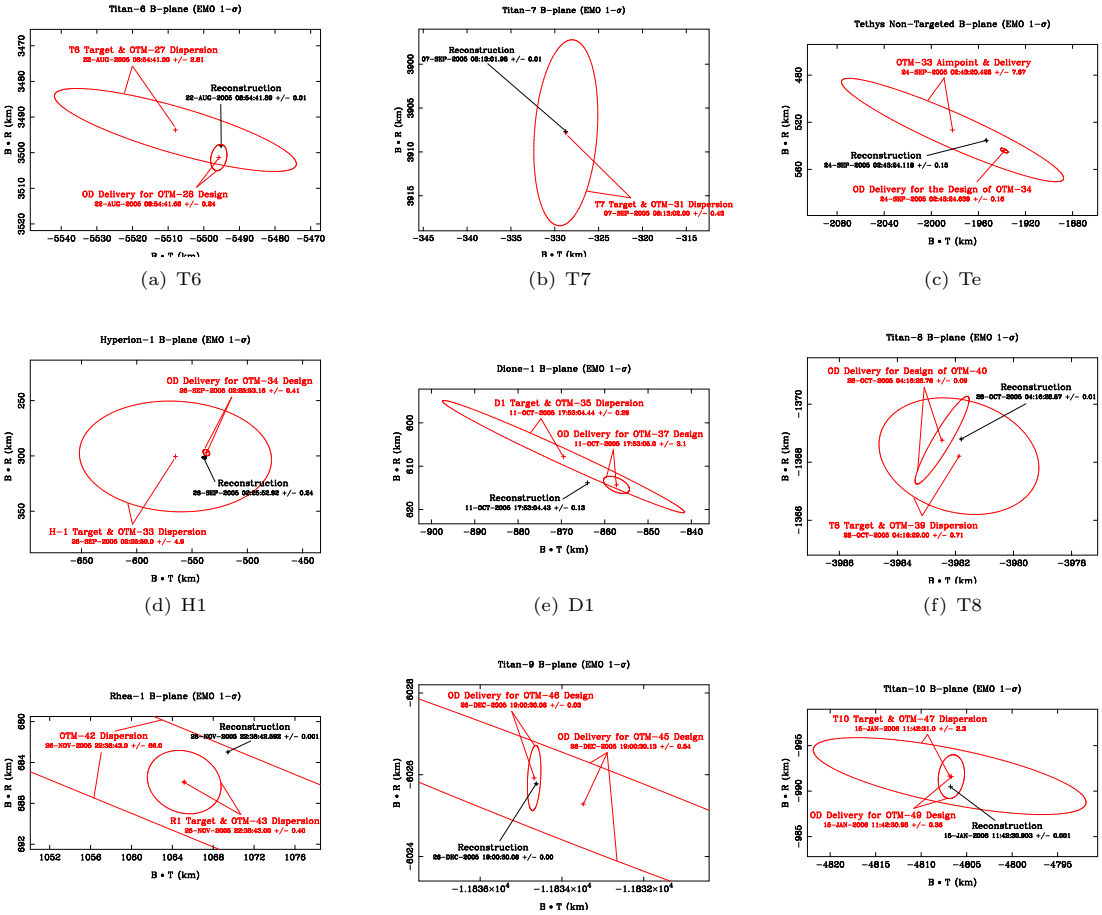
Table 4 Encounter Summary of Targeted Encounters (**Error given in terms of formal (unscaled) statistics**)

Target	Last Control Point	Last Maneuver Design	Maneuver Error	Nav or OD Error?	3D Position Error (km)	3D Bplane Error (σ)	Delivery Accuracy Probability	Reason for Miss
Titan-6	-5 day	OTM-28	Cancelled	OD	3.6	0.96	20%	
Titan-7	-3 day	OTM-31	$< 1\sigma$	Nav	0.190	0.18	0.2%	
Hyperion-1	-6 day	OTM-33	$< 1\sigma$	Nav	30.6	0.63	5.1%	
	-3 day	OTM-34	Cancelled	OD	5.0	2.0	74%	18 km Tethys eph error ($\sim 3\sigma$)
Dione-1	-13 day	OTM-35	$< 1\sigma$	Nav	16.1	2.5	90%	6.6 km Dione eph error ($\sim 2\sigma$)
	-3 day	OTM-37	Cancelled	OD	6.7	2.5	90%	
Titan-8	-10 day	OTM-39	$< 1\sigma$	Nav	2.4	0.7	7.9%	
	-3 day	OTM-40	Cancelled	OD	1.1	N.A.	N.A.	
Rhea-1	-3 day	OTM-43	$< 1\sigma$	Nav	6.0	2.4	88%	6 km Rhea eph error ($\sim 2\sigma$)
Titan-9	-7 day	OTM-46	Cancelled	OD	0.150	0.62	0.7%	
Titan-10	-7 day	OTM-49	Cancelled	OD	1.2	0.46	3.0%	

of these contributing error sources, except for the errors in the Dione ephemeris, were known before the D1 flyby. Nevertheless, the predicted D1 flyby errors were deemed by the Cassini project to be small enough that both of the maneuvers prior to D1 (OTM-36 and OTM-37) were canceled. Figure 8.e also compares the OD delivery for the OTM-37 design to the reconstructed trajectory. The 3-D B-plane error of this final OD prediction before D1 was 6.7 km, resulting in a 2.5-σ error. As with the other icy satellites, the opnavs did not provide information to determine Dione's orbit adequately prior to the flyby. A 6.6 km mainly down-track adjustment to Dione's orbit was observed after the flyby, which is about a 2.5-σ shift in its orbit with respect to the pre-flyby data. Consequently, the D1 encounter error can be attributed to the 6.7 km shift to Dione's ephemeris. The altitude achieved was 498.9 km.

Titan-8 (T8)

The post-D1 clean-up deterministic maneuver, OTM-38, fired with a ΔV of 14.8 m/s on October 12, 2005 to place the S/C back on track for the next Titan flyby (T8) with an altitude of 1353 km. The apoapsis OTM-39 burn (October 21, 2005) was then executed with a ΔV of 0.091 m/s to clean-up the errors of the fairly large OTM-38 burn. Since the difference between the OD delivery for the design of OTM-40 and the T8 target was small, the OTM-40 burn was canceled. The T8 encounter occurred on October 28, 2005 04:16:29 ET. The delivery B-plane from OTM-39 and the reconstructed trajectory are shown in Figure 8.f. Also shown on the plot are the OD solution and uncertainty at the OTM-40 data cutoff. As shown in Figure 8.f, the error between the reconstruction and the OTM-39 delivery was 0.6 km and -0.43 s in the B-plane. Since the error was mainly in the time-of-flight direction, this yielded a 3-D error of 2.4 km or 0.7-σ relative to the OTM-39 delivery dispersion. The 3-D B-plane difference between the reconstructed solution and the final OD pre-T8 solution (OD for OTM-40) was 1.1 km. Since this OD solution predicted a very small uncertainty in the time of flight of under 0.09 s, the 3-D error in terms of formal 1-σ statistics was not meaningful. This shift between the reconstruction and the OTM-40 OD solution was due to the mismodeling of the T8 RCS thrusting activity performed for radar mapping, which was poorly predicted at that time. The equivalent ΔV magnitude of this thrusting was approximately 1.65 m/s, which was equivalent to a medium-sized maneuver.



(a) T6 (b) T7 (c) Te

(d) H1 (e) D1 (f) T8

(g) R1 (h) T9 (i) T10

Figure 8 Encounter B-plane results (T axis lies in the Earth-Mean-Orbit plane) for the nine satellite flybys. Times are in spacecraft event time, ET-SCET (UTC + 64.2 s)

Rhea-1 (R1)

Three days after the T8 encounter on October 31, 2005 another fairly large maneuver, OTM-41 (ΔV = 12.4 m/s), was performed to clean-up the T8 flyby errors and place the S/C towards the next icy satellite, Rhea-1 (R1), 28.5 days later. This maneuver was designed together with the apoapsis maneuver, OTM-42 (ΔV = 2.13 m/s), which was executed on November 13, 2005. The final approach maneuver, OTM-43, required only 0.060 m/s to correct the trajectory three days before the R1 flyby. The R1 encounter occurred on November 26, 2005 22:38 ET. The error between the reconstruction and the OTM-43 target was 5.2 km and 0.4 s in the B-plane (Figure 8.g). This error yielded a 3-D error of 6.0 km or 2.4-σ. This was found to be mainly due to the errors in the pre-encounter Rhea ephemeris, which was determined to be in error 6 km along the down-track direction. The Rhea flyby was the first encounter to have continuous radio-metric tracking coverage because of the radio-science gravity harmonic experiment. We found it necessary to estimate the lower degree and order gravity harmonics (J2, C22 and S22) in order to produce stable solutions, especially for the Rhea ephemeris. Our estimates of these terms are reported in Ref.[9]. The achieved altitude at R1 was 502.0 km.

Titan-9 (T9)

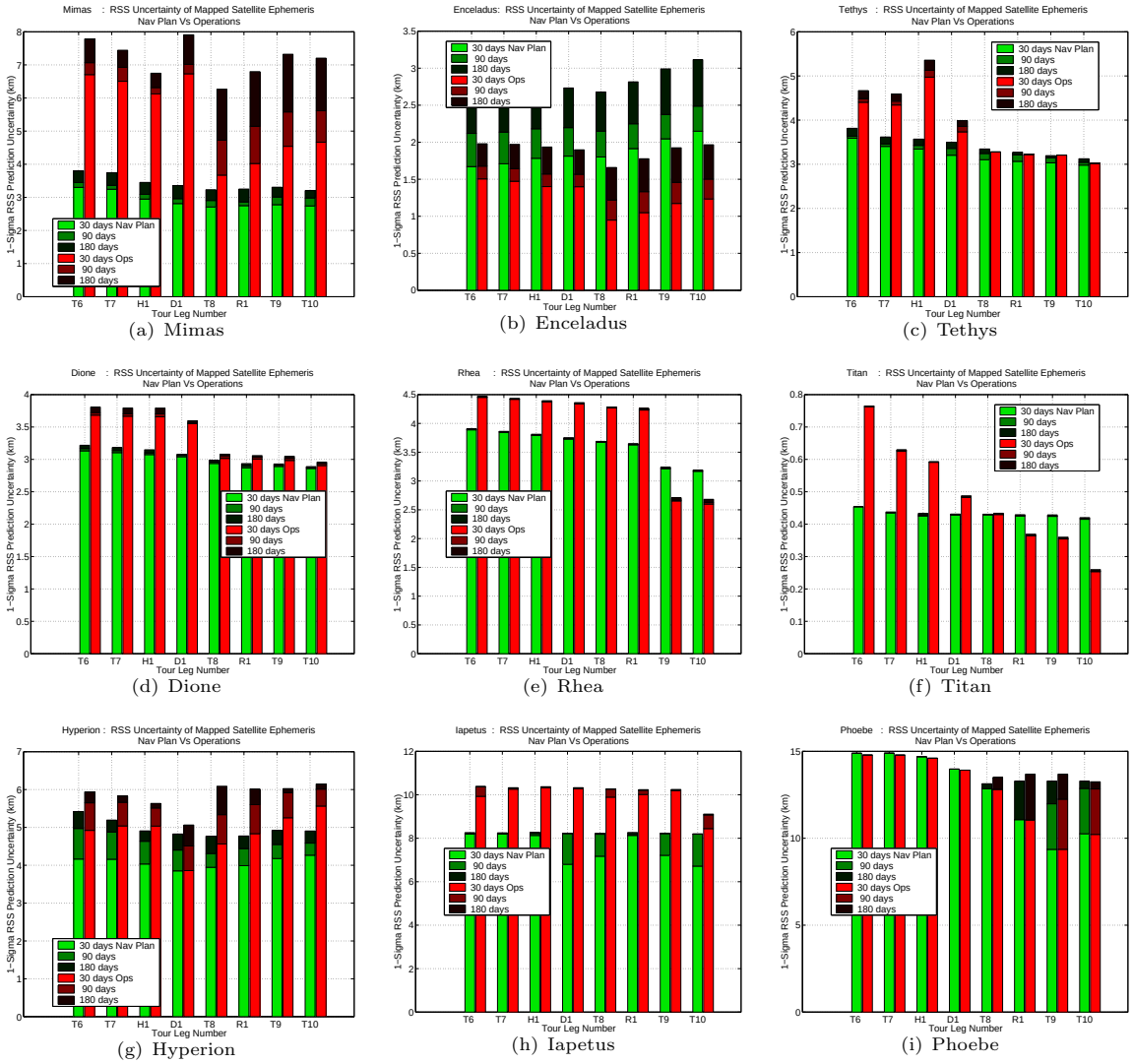
The OTM-44 data cutoff occurred approximately nine hours after the Rhea flyby with only 2 hours of post-encounter data. OTM-44 and OTM-45 were designed together in a chained-maneuver-optimization strategy[7] to target the 10,411 km altitude Titan-9 encounter (T9), which occurred approximately 30 days later on December 26, 2005 19:00:30 ET. The final targeting maneuver, OTM-46, was scheduled to fix OD and maneuver errors before the T9 encounter. The 0.24 m/s OTM-44 was designed to target an intermediate state for the purpose of reducing the propellant required to achieve the T9 encounter target. OTM-44 performed nominally and the post-OTM-44 OD solution mapped to the T9 B-plane was within the expected dispersion. However, the post-OTM-44 OD solution was sufficiently close to the T9 (OTM-46) target that it was determined that science observations and tour navigation were not sensitive to the difference between the post-OTM-44 OD and the T9 target, resulting in the cancellation of OTM-45. OTM-46 then became unnecessary and was also canceled. Figure 8.h shows the OD deliveries at the time of both the OTM-45 and OTM-46 designs along with the reconstructed T9 flyby. The original T9 final target is not shown but lies approximately 15 km above the reconstructed flyby. Figure 8.h illustrates the OD solution and associated uncertainty used for OTM-46 cancellation along with the flyby reconstruction and indicates excellent agreement between the two. The 3-D B-plane error of the reconstruction compared to the final pre-encounter OD (OTM-46 design OD) was 0.15 km or 0.6-σ.

Titan-10 (T10)

After the T9 encounter, the spacecraft was again placed on course for another Titan encounter, Titan-10 (T10), 20 days later. The T10 encounter, which occurred on January 15, 2006 11:43 ET, used a slightly different maneuver strategy than the nominal strategy described for the T9 encounter. The tight timeline associated with the outbound-to-inbound Titan transfer made it desirable to remove the apoapsis maneuver, OTM-48. Analysis conducted before the arc showed that the effect of removing the maneuver was small, and thus the maneuver was cancelled prior to the beginning of the arc. Thus, the T10 encounter was targeted directly by OTM-47 ($\Delta V = 0.18$ m/s) rather than using a chained-maneuver-optimization strategy. The delivery from OTM-47, the final OTM-49 OD delivery, and the reconstructed solution, mapped to the T10 B-plane, are shown in Figure 8.i. The OTM-47 target uncertainties were a combination of OD and maneuver execution errors. The offset between the OTM-49 OD delivery and the T10 target was remarkably small and they are indistinguishable at the scale of the plot. The maneuver design was far too small to even be considered and thus OTM-49 was cancelled. The difference between the reconstruction and the OTM-49 OD delivery was 1.1 km in the B-plane and 0.08 s in the time of closest approach (TCA). This error yielded a 3-D error of 1.2 km (0.46-σ).

SATELLITE EPHEMERIS DEVELOPMENT

Figure 9 compares the reduction of the satellite ephemeris position 1-σ uncertainties in operations between a tour OD covariance study performed several months prior to T6 (Revised Nav Plan)[10] and the formal 1-σ uncertainties achieved during operations. The satellite position uncertainties are mapped beyond the data cut off 30, 90 and 180 days for each data arc to determine whether the errors grow with time. Since these uncertainties osculate during the course of the satellites' orbits, the maximum values are used. Only the operational solutions for Mimas position uncertainties, which have been reduced to 7 km as shown in Figure 9, do not achieve the predicted $3-4$ km levels of the updated Nav Plan study. The operational ephemeris errors for the other satellites show good agreement to this updated study. Enceladus 1-σ errors remain within 2 km after 180 days. Tethys, Dione and Rhea position errors are shown to remain at the 3 km level with no apparent growth after 6 months. The orbit of Titan, as shown in Figure 9, has been well determined with 1-σ errors below 300 m after T10 arc. Also shown in Figure 9, Hyperion, Iapetus and Phoebe's position 1-σ errors are known, respectively, to approximately 6 km, 9 km and 14 km.



(a) Mimas (b) Enceladus (c) Tethys

(d) Dione (e) Rhea (f) Titan

(g) Hyperion (h) Iapetus (i) Phoebe

Figure 9 Comparing the operational satellite uncertainties against the Revised Nav Plan as satellite tour progresses.

As mentioned previously, the epoch states of each of the nine major satellites along with the Set III Saturn ephemeris parameters are included in the estimate list. The *a priori* values and covariances for these parameters are usually taken from a previous arc delivery with a data cutoff at the current arc epoch. Periodically, the OD team was provided with an update to the Saturn and Satellite ephemerides based on more extensive analyses to be used rather than the previous arc solution.[11 ,12] These satellite solutions were believed to be more reliable because it was made using a much larger data set. These solutions included ground based observations beginning in 1938, Hubble observations, Voyager 1 and 2 data, Pioneer 11 data, as well as all of the Cassini data taken to date.

The ephemeris estimates for several of the satellites have significantly changed since the first year of the Saturn tour[1] . This is due to the fact that only Phoebe, Titan, Iapetus, and Enceladus were flown by during the first year of the tour. Although, we did collect opnavs of all nine of the major satellites, the opnavs alone do not provide enough information to accurately determine the satellite orbits. Analysis of the opnav residuals has shown that all of the satellites opnavs consistently contain biases in the Sun-to-Satellite direction, which necessitates estimating the phase biases. There are other factors that tend to weaken the opnav data for particular satellites. For Phoebe, the problem is that virtually all of the opnavs taken at close range were when the satellite was at the same spot in its orbit since Phoebe orbits Saturn with a period of more than 500 days. For Titan, the thick and variable atmosphere creates problems in accurately finding the center of the body in the opnav image. For Iapetus, the drastic albedo variation also causes problems in finding the center of the opnav images. For Hyperion, the non-spherical shape along with the unpredictable rotational state of the body causes center finding problems, as well. These factors all conspire to make determining the satellite orbits difficult until they are flown-by at close range, at which time the radio-metric data provide an accurate anchor point for the satellite location at the time of the flyby.

In order to see how the estimated satellite trajectories have changed during this phase of the Cassini tour, Figure 10 compares each of the satellite trajectories during this time span. The comparisons are made between the last solution made before this phase of the tour (just after the Enceladus-2 flyby) and the final solution made at the end of this phase (just after the Titan-10 flyby). The differences are plotted in a Radial, Transverse, Normal coordinate frame relative to the Saturn Barycenter.

The mean of the Mimas differences during this time span was close to 18 km, with the largest differences being in the transverse and radial directions. Mimas has not had a close flyby to date, meaning that the current estimates are still more uncertain than for other satellites. A reason for the significant change in the estimated ephemeris is that we did flyby Tethys during this phase, which caused a correction to the Tethys estimated ephemeris. This caused the Mimas estimates to change because of the resonance between the Mimas and Tethys orbits. The mean of the Tethys correction during this phase is approximately 22 km, again mainly in the transverse and radial directions as shown in Figure 10.c.

There were already two Enceladus flybys prior to this phase of the Cassini tour, making the ephemeris estimates more accurate. This is reflected in Figure 10.b, which shows that the mean change in the trajectory during this phase was less than 3 km. The majority of this shift was due to the correction that was made to the estimated Dione trajectory after the Dione flyby, that occurred during this phase. Like Mimas and Tethys, there was a resonance in the orbits of Enceladus and Dione. The mean of the Dione corrections during this phase was close to 16 km. The majority of the difference was in the transverse directions, although there were significant changes in the radial and normal directions, as well.

The estimates for the Titan ephemeris showed the least amount of change during this phase of the Cassini tour. This was due to the fact that the previous phase of the tour contained several Titan flybys, so the trajectory of Titan was well known prior to the start of this phase. The mean difference during this time span is less than 1 km. Due to its proximity to Titan, the Hyperion orbit is perturbed significantly by Titan. This might have contributed to improving the estimate of the Hyperion ephemeris before the actual Hyperion flyby. As shown in Figure 10.g, the mean corrections

in the Hyperion trajectory were on the order of 5 km during this time span, even though this phase contained the first Hyperion flyby. Interestingly, the corrections were mainly in the transverse and normal directions, but not in the radial direction.

The significant changes to the estimates of the Iapetus and Phoebe trajectories is somewhat harder to explain. As noted above, the opnavs do not provide very strong information for either of these satellites. In the case of Iapetus, it may be that the mean changes of about 11 km simply reflect the true level of uncertainty in the current estimates. Likewise for Phoebe, the mean difference 18 km could also indicate the level of accuracy in the solutions. Although, some of the Phoebe changes could also be actual improvements in the estimated ephemeris. The Phoebe opnavs collected during this phase gave a wider distribution of data points with Phoebe at different longitudes in its orbit about Saturn. On the other hand, they were not very frequent and the range to Phoebe was so great that they only slightly influenced the Phoebe ephemeris. In Figure 9.i, the Phoebe ephemeris shows improvements after the D1 and R1 flybys. This may have been caused by improvements in the Saturn barycenter ephemeris brought about by improvements in the ephemerides and masses of Rhea and Dione.

ESTIMATION OF THE SATURNIAN MASSES

Figures 11 and 12 show the progression of the estimates and associated uncertainties of the Saturn system and Saturn satellite GMs[†], respectively, with time as a function of the OD solutions delivered to support operations. Also plotted in these figures are the values from the post-flyby solution reconstructions. These estimates and uncertainties were refined from data arc to data arc as each satellite flyby occurs and were also affected by the occasional updates to the extensive satellite OD analysis.[11 ,12]

In Figure 12.b, one can see the effect of the Enceladus E2 flyby is to cause an almost 1-σ shift in the GM estimate. In Figure 12.e, one can see how the Rhea flyby (during which continuous tracking was available) caused a greater than 1-σ shift in the estimate and reduced the uncertainties such that the error bars are not visible (the reduction in Rhea's GM uncertainty was actually greater than one order of magnitude). However, other features on this and other satellite's plots show abrupt changes, which are not associated with a single flyby event. These abrupt changes usually occurred when an updated satellite ephemeris and covariance was introduced from the extensive analyses describe above. At the end of September, after the Tethys and Hyperion flybys and before the Dione flyby, the extensive satellite OD analysis performed by Jacobson[‡] included ring occultation data to directly determine the Saturn pole. This caused changes in the inner satellites' GM estimates in particular as can be seen in Figure 12. Similarly, the introduction of opnav observations of minor satellites (one, Methone, in resonance with Mimas) provided an additional measure of the inner satellite's GMs at the start of November. Often, after a flyby, a new satellite ephemeris is used, which incorporates the effects of the flyby and other data as well as refinements to the satellite OD filter and modeling set-up such as can be seen in these figures after the Titan-8 flyby.

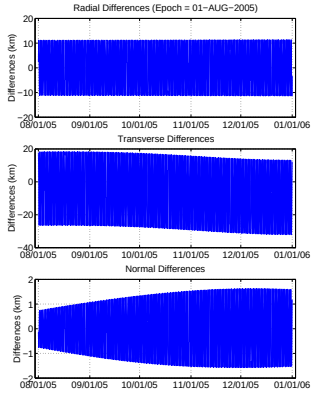
Mimas and Iapetus remain the only satellites to not have close flybys. There will be no close flyby of Mimas in the prime mission, but a close Mimas flyby is of interest for science and is being considered in the extended mission plans. A 1000 km flyby of Iapetus is planned for September 2007, although as explained by Antreasian et al., 2005 (Ref. [1]), the Iapetus mass is already well determined. The latest Saturn and satellite mass estimates after the T10 flyby are shown in Table 5. These estimates of the satellite and Saturn masses have been determined to much less than 0.5%.

POINTING PREDICTION PERFORMANCE

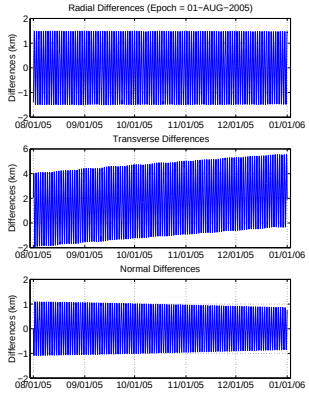
To properly prepare for the instrument observations during these close satellite encounters, the OD team produced a set of pointing predictions (vectors from S/C to nadir location on satellite) and

[†] GM represents the product of the gravitational constant and the mass of the body

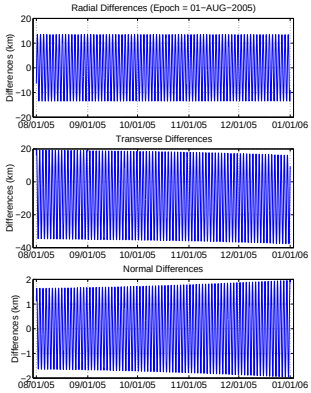
[‡] R.A. Jacobson, private communications, Sep. 2005



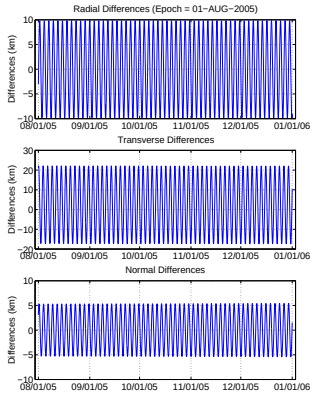
(a) Mimas



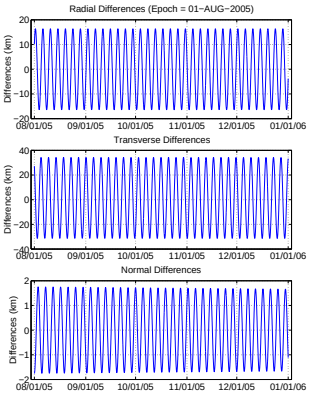
(b) Enceladus



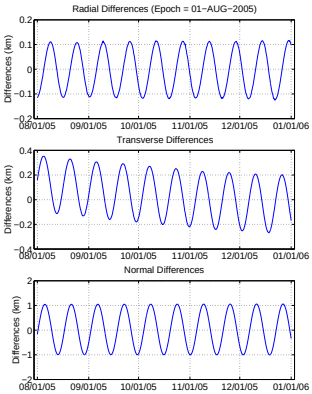
(c) Tethys



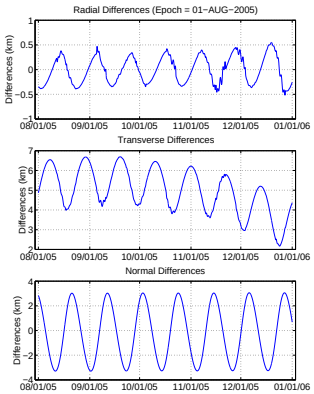
(d) Dione



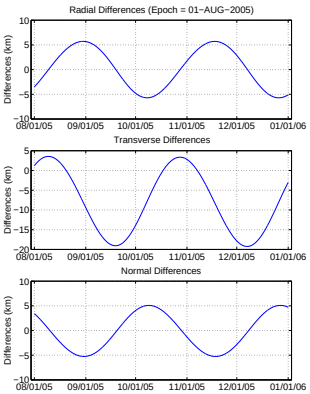
(e) Rhea



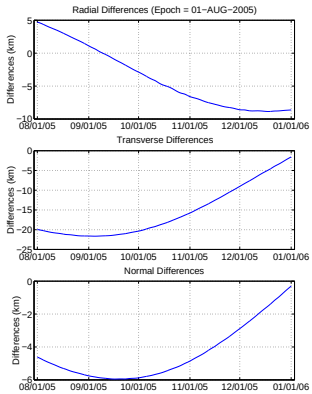
(f) Titan



(g) Hyperion



(h) Iapetus



(i) Phoebe

Figure 10 Comparing the Pre-E2 and the Post-T10 satellite ephemerides

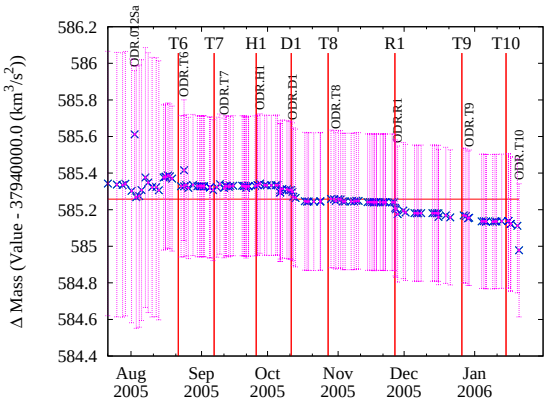
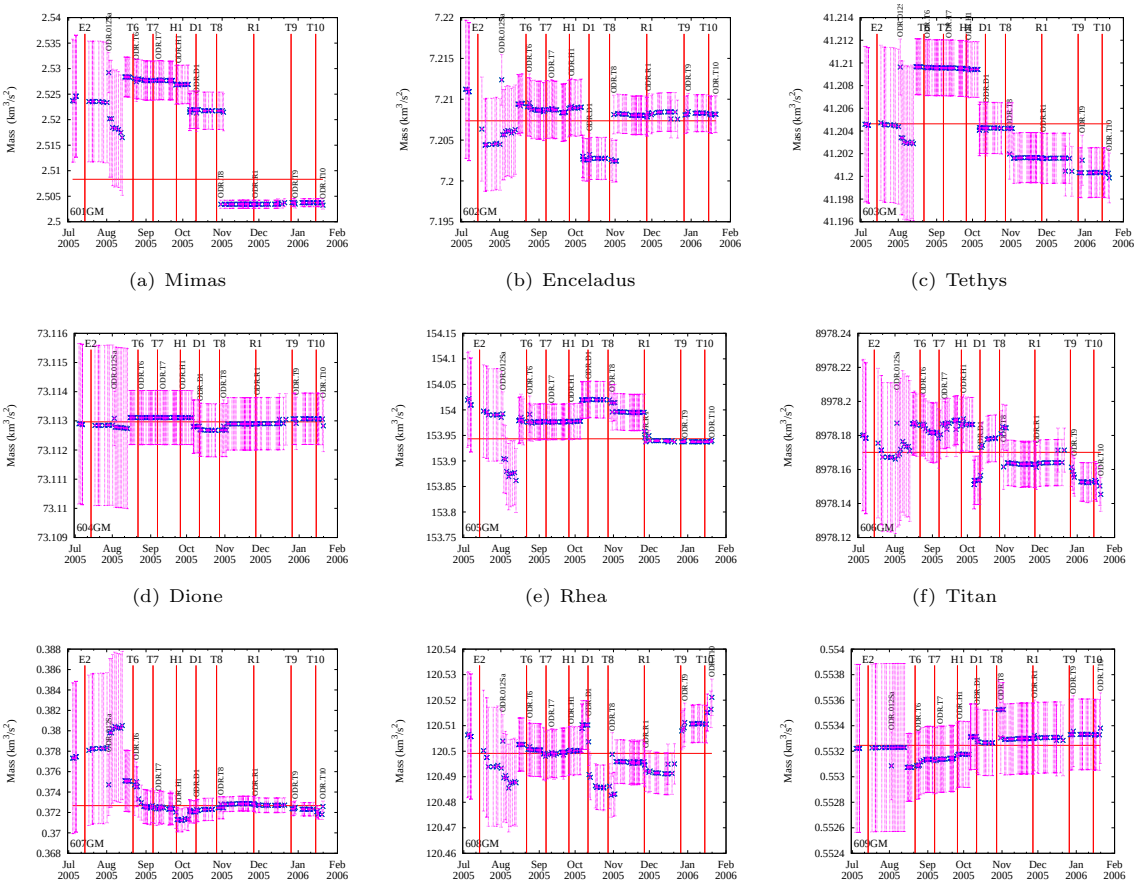


Figure 11 Saturn Mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

Table 5 Saturn System and Satellite Masses after the Titan-10 flyby

Body	GM (km^3/s^2)		
System	37940585.0	±	0.4
Saturn	37931207.5	±	0.4
Mimas	2.5033	±	0.0008
Enceladus	7.208	±	0.002
Tethys	41.200	±	0.002
Dione	73.113	±	0.001
Rhea	153.940	±	0.002
Titan	8978.14	±	0.01
Hyperion	0.3726	±	0.0005
Iapetus	120.521	±	0.007
Phoebe	0.5533	±	0.0003



(a) Mimas (b) Enceladus (c) Tethys

(d) Dione (e) Rhea (f) Titan

(g) Hyperion (h) Iapetus (i) Phoebe

Figure 12 Satellite Mass (GM) estimates and uncertainties from operational, reconstructed (labeled) OD solutions versus time.

uncertainties based on either the OD solution (in the case of a canceled approach maneuver) or the control solution (which includes the maneuver that targets the trajectory to the desired aim point and its dispersion) to the science teams. These predictions are used to verify or update instrument-pointing vectors in the onboard sequence to ensure the success of the science observations. Table 6 lists the error of the predicted pointing at the 20,000 and 30,000 km altitudes which are used as the basis for the requirements (for both the inbound and outbound directions) along with the uncertainty in the pointing predictions. The non-targeted Tethys encounter was the only one to exceed the pointing requirements of 1.02 and 0.79 mrad, respectively, for the 20,000 and 30,000 km altitudes. As shown in Table 6, the predicted-pointing errors for all Titan flybys were well under 1-σ (by comparing the prediction error to the predicted uncertainty) except for the outbound leg of T8 which was about 1-σ. The predicted-pointing solutions for Hyperion, Dione and Rhea were in error, respectively, by approximately 1.5-σ, 2.1-σ, and 1.3-σ, however, these errors were relatively small and did not impact the science observations.

Table 6 Encounter Predicted Pointing Uncertainty and Error

Encounter		Inbound 30,000 km (mrad)	Inbound 20,000 km (mrad)	Closest Approach (mrad)	Outbound 20,000 km (mrad)	Outbound 30,000 km (mrad)
Titan-6	Predicted Uncertainty	0.142	0.227	0.854	0.204	0.149
	Prediction Error	0.117	0.178	0.415	0.153	0.111
Titan-7	Predicted Uncertainty	0.429	0.720	3.189	1.114	0.835
	Prediction Error	0.004	0.006	0.038	0.012	0.009
Tethys	Predicted Uncertainty	3.511	5.477	61.850	5.108	3.458
	Prediction Error	1.027	1.613	17.889	1.389	0.966
Hyperion-1	Predicted Uncertainty	0.111	0.165	7.654	0.165	0.109
	Prediction Error	0.160	0.241	5.460	0.244	0.164
Dione-1	Predicted Uncertainty	0.108	0.164	6.342	0.165	0.108
	Prediction Error	0.219	0.329	4.135	0.341	0.228
Titan-8	Predicted Uncertainty	0.065	0.102	1.227	0.049	0.033
	Prediction Error	0.015	0.022	0.314	0.051	0.032
Reah-1	Predicted Uncertainty	0.126	0.192	6.988	0.204	0.139
	Prediction Error	0.172	0.261	4.446	0.248	0.164
Titan-9	Predicted Uncertainty	0.027	0.042	0.070	0.045	0.028
	Prediction Error	0.004	0.006	0.008	0.007	0.005
Titan-10	Predicted Uncertainty	0.089	0.139	1.306	0.136	0.096
	Prediction Error	0.037	0.055	0.247	0.032	0.014

CONCLUSIONS

Including post-flyby radio-metric data in the OD filter allow for reconstructions of the targeted B-plane coordinates, which have been within one formal sigma of the target control dispersion in several cases, as shown in Table 4. The Titan encounters are shown to be especially accurate, all under 1-σ. The first flybys of the icy satellites have been more challenging since we have relied on Cassini's optical navigation images and the satellite-to-satellite correlations to determine their orbits beforehand. As such, the radio-metric data during these encounters have determined approximately 2-σ shifts in the positions of Dione and Rhea ($\approx 6 - 7$ km) at these times (table 4). The achieved altitudes of all targeted flybys were under 5.3 km from the predicted or controlled altitudes. Unprecedented accuracy in Cassini's navigation have resulted in targeting errors for two of the recent Titan flybys to be less than 300 m. The masses of Saturn and its satellites have been determined to much less than 0.5%. The pointing solutions used for science observations exceeded in most cases the requirements and the error in their predictions were under 1-σ nearly all the Titan flybys. The performance of the Cassini OD along with accurate maneuver designs[7] and their executions[7] have led to the cancelation of ten planned statistical maneuvers (listed in Table 3).

ACKNOWLEDGEMENTS

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

The authors wish to thank Sean Wagner and Paul Thompson for their comments and thorough reviews of this paper.

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