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This paper documents the maneuvers performed by the Cassini spacecraft in its first year of Saturn tour. Since Saturn arrival, the spacecraft has made several flybys of Saturn's satellites and has delivered the Huygens probe to Titan. Of the 20+ maneuvers executed since Saturn orbit insertion, the Periapsis Raise Maneuver, the Probe Targeting Maneuver, and the Orbiter Deflection Maneuver were the most defining. Highlights of this paper include the maneuver strategies for tour and a preliminary analysis of the execution errors of maneuvers performed to date. In its first year orbiting Saturn, Cassini has been navigated with amazing success.

INTRODUCTION

After a nearly seven-year-long journey to Saturn, the Cassini-Huygens spacecraft was inserted into a Saturnian orbit on 1-Jul-2004, beginning its four-year tour of Saturn and its many moons. Since the Saturn Orbit Insertion (SOI) maneuver, the spacecraft has made several close flybys of Titan, Saturn's largest moon, and Saturn's icy satellites and has delivered the European Space Agency's (ESA) Huygens probe to Titan. This paper documents the maneuver experience during the first year of the Cassini-Huygens mission at Saturn. In addition, the execution error statistics of maneuvers from launch to the end of the first year of Saturn tour are analyzed. Earlier papers reported on the maneuver experience during early interplanetary cruise[1] and inner cruise.[2] A concurrent paper details the maneuver experience from the end of cruise to the arrival at Saturn.[3]

Of the over twenty Orbit Trim Maneuvers (OTMs) that were executed since SOI, the Periapsis Raise Maneuver (PRM or OTM-002), the Probe Targeting Maneuver (PTM or OTM-008), and the Orbiter Deflection Maneuver (ODM or OTM-010) were the most defining in the first year of Saturn tour. PRM was performed in August 2004 to set up the first Titan encounter by raising the ascending node crossing from between the F and G rings to near Titan's orbit. This maneuver also established the orbital eccentricity needed for the spacecraft to target Titan in subsequent flybys, including the Titan encounter for the Huygens probe delivery. After two flybys of Titan, the PTM maneuver was executed in December 2004 to target the combined Cassini-Huygens spacecraft to Titan for the Huygens probe release. On Christmas Day 2004, the probe was released from the spacecraft and began its three-week journey to Titan. ODM was performed 3 days later to deflect the Cassini orbiter away from its impact trajectory and also to delay and position its closest

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approach to Titan for probe relay. On 14-Jan-2005, the Huygens probe made a successful descent and relayed data back to Earth via the Cassini orbiter. Figure 1 shows the planned trajectory from Saturn approach through the Huygens probe mission.

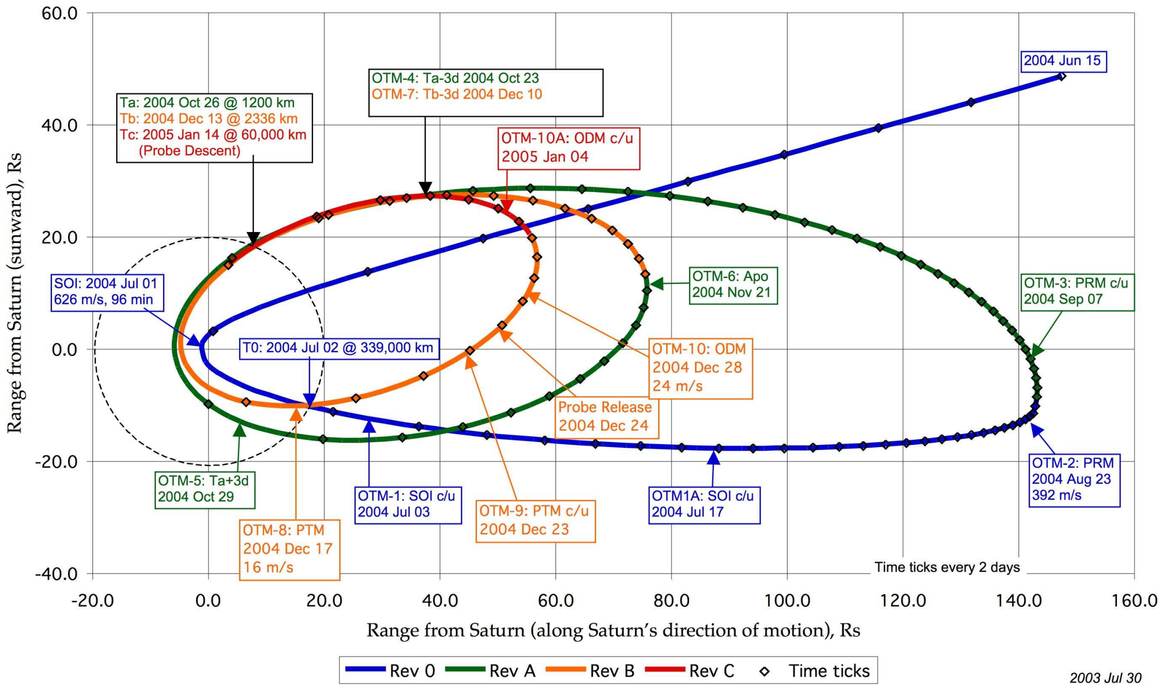


Figure 1 Saturn Approach through Huygens Probe Mission. *Source: Cassini Mission Plan, Ref. [4]. Note, some of the maneuvers listed were cancelled.*

MANEUVER EXECUTION

The Cassini tour of Saturn was designed to take advantage of the substantial gravity assists provided by each Titan flyby, with closer flybys imparting larger ΔVs to the spacecraft. For instance, a Titan flyby at an altitude of 950 km supplies an equivalent ΔV of about 800 m/s to the spacecraft. During tour, propulsive maneuvers are necessary not only to correct the spacecraft's trajectory due to flyby dispersions, but also to change the trajectory when Titan gravity assists are not sufficient. Maneuvers are accomplished through the use of two independent propulsion systems. The bi-propellant main engine assembly (with two main engines MEA and MEB) performs large maneuvers, while the Reaction Control System (RCS) thrusters handle small trajectory corrections.[5] A "cut-off" criterion for the main engine of 0.4 m/s has been adopted for choosing either main engine or RCS for a maneuver (i.e., a maneuver greater than 0.4 m/s would generally be performed on main engine). Main engine MEA has been used for every main engine burn since launch. The spacecraft coordinate system for the Cassini spacecraft is labeled in Figure 2: $X_{S/C}$, $Y_{S/C}$, and $Z_{S/C}$. The $Z_{S/C}$ axis points from the high gain antenna to the main engine, the $X_{S/C}$ axis points away from the probe (shown on the left side of the spacecraft in Figure 2), and the $Y_{S/C}$ axis completes the right-handed system.

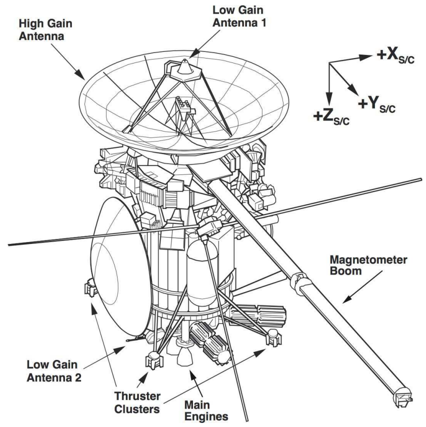


Figure 2 Cassini-Huygens Spacecraft

Maneuver execution errors are modeled using the Gates model.[6] The Gates model accounts for four independent error sources, fixed and proportional magnitude errors (σ_1, σ_2) and fixed and proportional pointing errors (σ_3, σ_4). Assuming a Gaussian distribution, each parameter represents the standard deviation for that error source and each error source is assumed to have a zero mean. Table 1 shows the 1-σ execution error model used for main engine and RCS during the first year of tour and throughout most of the cruise to Saturn. This model was last updated from the analysis of maneuvers during the interplanetary cruise.[2] Section "Execution Error Model" presents a new study of the execution error statistics using maneuvers from the cruise and the first year of the Saturn tour.

Table 1
MANEUVER EXECUTION ERROR MODEL (1-σ)

		Main Engine	RCS
Magnitude	Proportional (%)	0.2	2.0
	Fixed (mm/s)	10.0	3.5
Pointing (per axis)	Proportional (mrad)	3.5	12.0
	Fixed (mm/s)	17.5	3.5

Several ΔVs associated with a maneuver contribute to the total ΔV imparted to the spacecraft. These include, but are not limited to, deadband tightening, roll and yaw turns, pointing-bias-fix turns*, the burn itself, and Reaction Wheel Assembly (RWA) / RCS transitions. Generally, only the burn and turn ΔVs are considered as the total ΔV, with the other ΔV events added when analyzing the execution errors.

MANEUVER STRATEGY

The maneuver strategy since launch has been to target the spacecraft to encounter conditions defined in the reference trajectory. With the exception of the Titan-B (Tb) to Titan-C (Tc) orbit for the Huygens probe mission (see "Titan-B to Titan-C Flyby" section), the control of the spacecraft trajectory has been accomplished with three propulsive Orbit Trim Maneuvers (OTMs) between each targeted encounter: a flyby cleanup maneuver and

*These are also referred as the 7OFFSET turns, named after the flight software command (see Ref. [2]).

two targeting maneuvers. Usually performed three days after an encounter, the cleanup maneuver is used to correct errors from a previous flyby. The first targeting maneuver to a flyby is performed near the apoapsis of the orbit, usually with a substantial deterministic component for "shaping" the orbit. The last targeting maneuver is generally executed three days before an encounter to cleanup the errors from the near-apoapsis maneuver and to achieve as accurate flyby conditions as possible. This strategy of 3 maneuvers per encounter will usually be implemented throughout the tour. Figure 3 illustrates this maneuver strategy for an inbound-to-inbound Titan transfer. Except for the Tb to Tc flyby, this maneuver technique was followed for each satellite encounter.

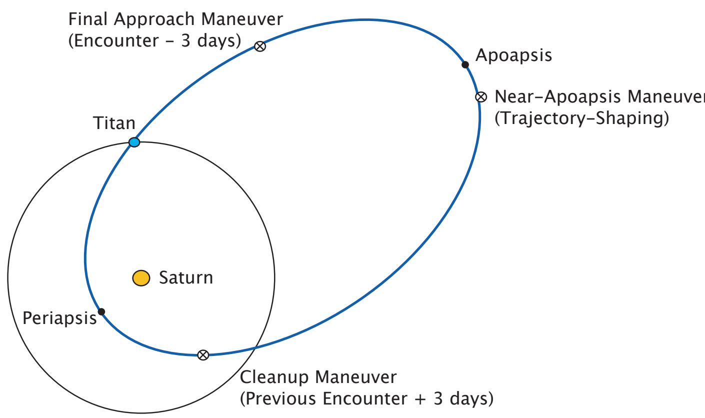


Figure 3 Maneuver Strategy for Saturn Tour

Maneuvers are generally targeted to three flyby parameters in the B-planes of upcoming encounters, specifically the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$ and the time-of-flight component (for a discussion on B-planes, see "Appendix: B-Plane Description"). The flyby cleanup maneuvers, however, are designed with a chained two-impulse optimization strategy, which couples the first two maneuvers in a leg (in this case, the cleanup and near-apoapsis maneuvers) across several encounters. Since this optimization strategy did not become standard until after the Huygens probe mission, it will not be discussed in detail until the section "Titan-3 through Enceladus-2 Flyby."

MANEUVER EXPERIENCE

From SOI (1-Jul-2004) to OTM-025 (8-Jul-2005), there were a total of 21 maneuvers performed and 6 maneuvers cancelled. Table 2 gives the performance history of these maneuvers in terms of ΔV, grouped by encounter arcs. Each ΔV value listed is the sum of the burn and turns ΔVs. The turn ΔVs are the roll and yaw turns associated with orienting the spacecraft for the burn, including the pointing-bias-fix turns. The predicted deterministic ΔVs refer to the required deterministic ΔVs in the reference trajectory. The predicted mean and $\Delta V95^*$ values were determined from hi-fidelity Orbit Determination (OD) covariance studies using the latest reference trajectories and the Gates execution error model in a Monte Carlo simulation via LAMBIC.[7] These predicted values account for both maneuver and OD statistical variations. The design ΔVs listed are the ones that were used to command the spacecraft. These ΔVs were computed using a non-linear

$^*\Delta V95$ indicates that 95% of the time, the maneuver ΔV size will be less than this value.

search path varying program (SEPV) that satisfies a given set of encounter conditions. The reconstructed ΔVs were determined by the OD reconstruction of the trajectory after the maneuvers were performed. Since the differences between the reconstructed and design ΔVs were small, the reconstructed ΔVs were chosen in the comparison to the predicted ΔVs to determine the predict errors. Hence, the predict errors are quantitative measures of how well the reconstructed ΔVs (or equivalently the design ΔVs) matched the predicted values in numbers of σ. As seen in the table, most maneuvers had a predict error under 2-σ. It can also be garnered from the design and reconstructed ΔV data that there was a fair balance of overburns and underburns*, with all of the RCS maneuvers being overburns.

Table 2

MANEUVER PERFORMANCE HISTORY

	Description/ Location	Predicted ΔV Det. (m/s)	Predicted ΔV Mean (m/s)	Predicted $\Delta V95$ (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Predict Error† (# of σ)	Burn Type
OTM-001	SOI-CU	0.0	5.340	12.830	*CANCELLED*			
OTM-001a‡	SOI-CU	0.0	1.080	8.010	*CANCELLED*			
OTM-002	PRM	391.73	391.75	393.38	392.95	393.05	1.302	MEA
OTM-003	PRM-CU	0.0	2.520	4.770	0.507	0.513	1.619	MEA
OTM-004**	Ta-3d	0.231	0.231	0.240	0.372	0.383	26.494	RCS
OTM-005	Ta+3d	0.238	0.835	2.041	0.655	0.646	0.300	MEA
OTM-006	Ta+apo	0.091	0.348	0.711	0.420	0.421	0.382	MEA
OTM-007	Tb-3d	0.0	0.124	0.328	*CANCELLED*			
OTM-008	PTM	11.917	11.931	12.070	11.937	11.929	0.029	MEA
OTM-009	PTM-CU	0.0	0.111	0.256	0.018	0.021	1.231	RCS
OTM-010	ODM	23.733	23.735	23.877	23.785	23.793	0.696	MEA
OTM-010a	ODM-CU	0.0	0.196	0.360	0.135	0.139	0.631	RCS
OTM-011††	Tc+2d	21.131	21.199	21.271	21.623	21.633	9.904	MEA
OTM-012††	Tc+apo	19.437	19.294	19.476	18.702	18.710	5.543	MEA
OTM-013	T3-3d	0.0	0.828	1.867	0.206	0.208	1.158	RCS
OTM-014	T3+3d	0.118	0.535	1.402	0.722	0.716	0.415	MEA
OTM-015	T3+apo	0.697	2.810	6.419	6.259	6.263	1.883	MEA
OTM-016	E1-3d	0.0	0.066	0.129	*CANCELLED*			
OTM-017	E1+3d	0.236	0.650	1.696	0.451	0.449	0.372	MEA
OTM-018	E1+apo	1.690	1.711	1.957	1.623	1.620	0.652	MEA
OTM-019	T4-3d	0.0	0.111	0.261	*CANCELLED*			
OTM-020	T4+3d	0.002	1.201	3.038	0.927	0.919	0.288	MEA
OTM-021	T4+apo	6.281	6.360	8.017	5.870	5.863	0.612	MEA
OTM-022	T5-3d	0.0	0.118	0.262	0.064	0.065	0.728	RCS
OTM-023	T5+3d	0.011	0.728	3.088	*CANCELLED*			
OTM-024	T5+apo	21.207	20.546	22.206	20.569	20.587	0.043	MEA
OTM-025	E2-5d	0.0	1.434	3.539	0.372	0.366	0.995	MEA

*In this paper, if the reconstructed ΔV is greater than the design ΔV, the burn is an overburn. Conversely, if the reconstructed ΔV is less than the design ΔV, the burn is an underburn.

†Predict Error = |Reconstructed ΔV - Predicted ΔV Mean| / Predicted ΔV σ.

‡OTM-001a was a contingency maneuver in case OTM-001 was aborted or performed insufficiently.

**Since the OTM-003 design did not account for a significant error in a predicted flight software test ΔV, OTM-004 was affected causing the large prediction error.

††Large prediction error since LAMBIC setup with OD hi-fidelity covariance study did not completely account for previous asymptote errors (i.e., asymptote errors already accumulated could not be included).

Table 3 lists the flyby errors for each encounter from Titan-A to Enceladus-2. There was a total of six targeted Titan flybys and two targeted Enceladus flybys during this time period. The target conditions, given in Earth Mean Orbital B-plane coordinates at the J2000 epoch, were used in the final maneuver designs. The flyby errors, which were the differences between the actual flybys and the designed, reveal that most encounters were within 10 km and a few seconds from predictions.

Table 3
TARGETED ENCOUNTER HISTORY

	Target Conditions (EMO2000)				Flyby Errors‡		
	B·R (km)	B·T (km)	Time of Closest Approach (TCA) (ET-SCET)*	Altitude† (km)	B·R (km)	B·T (km)	TCA (sec)
Titan-A	-1902	3571	26-Oct-2004 15:31:13	1200	-5.62	-32.05	-4.21
Titan-B	-2883	2841	13-Dec-2004 11:39:17	1200	-5.45	-17.00	2.54
Titan-C	-17828	-60305	14-Jan-2005 11:13:00	60000	-33.06	6.41	2.97
Titan-3	-1046	4305	15-Feb-2005 06:58:57	1577	-3.98	1.52	0.32
Enceladus-1	28	-747	09-Mar-2005 09:09:05	500	-1.50	-1.98	1.56
Titan-4	-4595	-2547	31-Mar-2005 20:06:20	2402	-5.55	6.07	0.15
Titan-5	-2882	2586	16-Apr-2005 19:12:50	1025	-3.94	-0.79	0.13
Enceladus-2	-32	-421	14-Jul-2005 19:56:26	175	4.83	2.11	-0.44

The designed characteristics of all maneuvers performed since SOI and up to OTM-025 are summarized in Table 4. These characteristics include the maneuver epoch, the cut-off time for the last radiometric data received by OD, the true anomaly of the spacecraft, the design ΔV size, the roll and yaw turn angles for spacecraft burn attitude, and the Earth-look angle. The true anomaly gives a picture of where the spacecraft is in the orbit at the time of the maneuver (e.g., at a value of 180°, the spacecraft is at the apoapsis of the orbit). From Table 4, it can be observed that only a few near-apoapsis maneuvers are actually near apoapsis (e.g., OTM-006 and OTM-018), but are still labeled as such for identification purposes. The roll and yaw angles are performed before each maneuver (roll-yaw "wind" sequence) to orient the spacecraft for the maneuver burn and after each maneuver (yaw-roll "unwind" sequence) to return to the pre-maneuver spacecraft orientation. The Earth-look angle is the angle between the total ΔV vector and a vector from the spacecraft to Earth (line-of-sight vector). This angle provides insight into the observability of a maneuver. If the look angle is 0°, the magnitude of the maneuver will be well estimated since it is fully observable on the Earth-line. If the look angle is 90°, then only one component of the pointing error will be well estimated.[2] It can be seen in Table 4 that the magnitude of the Earth look angle is approximately the same as the yaw turn angle. This is a consequence of the spacecraft being Earth-pointed prior to each maneuver for spacecraft health and safety verification, the uplinking of the maneuver, and the 2-way Doppler before the maneuver.

*Times given are in ephemeris time (ET) - spacecraft event time (SCET).
†Altitude not explicitly targeted in maneuver designs.
‡Reconstructed Flyby Conditions - Target Conditions

Table 4
MANEUVER DESIGN CHARACTERISTICS

	Maneuver Epoch (UTC-SCET)*	OD DCO† (days)	True Anomaly (deg)	ΔV (m/s)	Roll (deg)	Yaw (deg)	Earth Look (deg)
OTM-002	23-Aug-2004 15:53	-7.1	179.33	392.95	2.20	-32.19	31.19
OTM-003	07-Sep-2004 16:30	-4.9	-175.88	0.51	-165.01	-79.50	75.94
OTM-004	23-Oct-2004 06:16	-1.8	-134.83	0.37	66.27	-143.94	143.94
OTM-005	29-Oct-2004 06:15	-1.0	92.17	0.66	-120.22	-133.74	130.48
OTM-006	21-Nov-2004 05:00	-2.8	179.84	0.42	74.39	-154.93	151.35
OTM-008	17-Dec-2004 01:22	-1.4	131.68	11.94	17.88	-59.41	57.68
OTM-009	23-Dec-2004 00:52	-1.4	163.90	0.02	-72.26	-79.21	79.21
OTM-010	28-Dec-2004 00:37	-1.5	174.43	23.79	111.46	-97.38	99.57
OTM-010a	03-Jan-2005 23:38	-1.3	-173.55	0.14	-124.09	-135.68	135.68
OTM-011	16-Jan-2005 09:20	-5.9	30.72	21.62	-110.02	-31.73	34.48
OTM-012	28-Jan-2005 07:08	-3.2	173.11	18.70	143.58	-20.75	23.63
OTM-013	12-Feb-2005 06:07	-3.1	-153.49	0.21	73.20	-129.71	129.71
OTM-014	18-Feb-2005 06:00	-1.3	133.14	0.72	-80.19	-84.05	85.00
OTM-015	02-Mar-2005 04:50	-1.8	-171.84	6.26	1.66	-99.95	101.88
OTM-017	12-Mar-2005 03:20	-1.3	151.27	0.45	-37.94	-75.06	75.38
OTM-018	19-Mar-2005 18:19	-2.5	-179.92	1.62	-153.35	-53.34	55.25
OTM-020	04-Apr-2005 02:22	-0.8	170.35	0.93	143.74	-99.17	100.31
OTM-021	10-Apr-2005 02:00	-2.0	-169.52	5.87	-172.16	-48.87	51.15
OTM-022	14-Apr-2005 02:40	-1.8	-134.83	0.06	99.66	-19.79	19.79
OTM-024	29-Apr-2005 00:58	-3.8	-161.00	20.57	0.72	-53.55	55.87
OTM-025	08-Jul-2005 20:37	-1.2	-169.66	0.37	101.91	-55.49	55.85

SOI to Titan-A Flyby: OTM-001, OTM-001a, OTM-002, OTM-003 & OTM-004

Following the Saturn Orbit Insertion (SOI) maneuver on 1-Jul-2004 to the targeted Titan-A (Ta) encounter on 26-Oct-2004, there were four planned maneuvers and one contingency maneuver, three of which were performed. OTM-001, also referred to as SOI cleanup (SOI-CU) and SOI+2d, was planned for 3-Jul-2004 to correct SOI's delivery to Saturn. The final maneuver design of OTM-001, which was targeted to an orbital period of 116 days at the time of OTM-002 (via the semi-major axis and inclination), yielded a ΔV of just under 2 m/s. From a past study, it was determined that for an OTM-001 size of 2 m/s or less there were no significant increases in the sum of downstream maneuver ΔV magnitudes or in the positional deviations from the reference trajectory.[8] Hence, OTM-001 was cancelled. OTM-001a (SOI+16d) was also considered for 16 days after SOI (17-Jul-2004) as a backup to OTM-001 in case it was aborted or performed insufficiently. The two-week gap between the two cleanup maneuvers was necessary in order to avoid any maneuver operations during or near the July solar conjunction. The maneuver strategy for OTM-001a would have involved coupling the maneuver with OTM-002 in an optimization chain.[9]

*Times given are in coordinated universal time (UTC) - spacecraft event time (SCET).
†OD data cutoff time (DCO) given in days relative to maneuver epoch.

OTM-002, also referred to as the Periapsis Raise Maneuver (PRM), was executed on 23-Aug-2004 near apoapsis. It was designed to raise the ascending node crossing from between the F and G rings (at 2.6 Saturn Radii) out to near Titan's orbit (at 20 Saturn Radii). This maneuver also established the orbital eccentricity needed to target Titan in subsequent flybys, including the Titan-3 (T3) encounter for the Huygens probe delivery. At 393 m/s, it was the largest maneuver in the nominal Saturn tour. Two weeks later, OTM-003, also known as PRM cleanup (PRM-CU), was performed on 7-Sep-2004 near apoapsis. It was designed to correct the errors in OTM-002 in targeting Ta. Since performing OTM-002 and OTM-003 were imperative in establishing a Titan-based tour and the changes in the OD solution near apoapsis were small due to the long orbit arc, the OD cutoff times of the radiometric data for these maneuvers were made earlier than usual (7 and 5 days prior to OTM-002 and OTM-003, respectively). Finally, OTM-004 (Ta-3d) was performed three days prior to the Ta encounter on 23-Oct-2004. Not only the first maneuver in the Saturn tour to be executed on RCS thrusters, it was the largest RCS burn performed to date at 383 mm/s.

Titan-A to Titan-B Flyby: OTM-005, OTM-006, and OTM-007

The standard 3-maneuver-per-flyby strategy was first employed during the Titan-A (Ta) to Titan-B (Tb) arc with maneuvers OTM-005, OTM-006, and OTM-007. OTM-005 (Ta+3d) was a main engine burn performed on 29-Oct-2004, three days after the Ta encounter, to clean up dispersions from that flyby. It was designed with OTM-006 via two-impulse optimization. OTM-006 (Ta+apo) was performed on 21-Nov-2004 near apoapsis with the main engine to target to the 1200 km Tb flyby on 13-Dec-2004. OTM-007 (Tb-3d) was scheduled for 10-Dec-2004, three days before the Tb encounter. The predict errors for both OTM-005 and OTM-006 were well under 0.5 σ and the execution errors of both maneuvers were small. Due to the excellent performance of OTM-006, OTM-007 was deemed unnecessary and consequently cancelled.

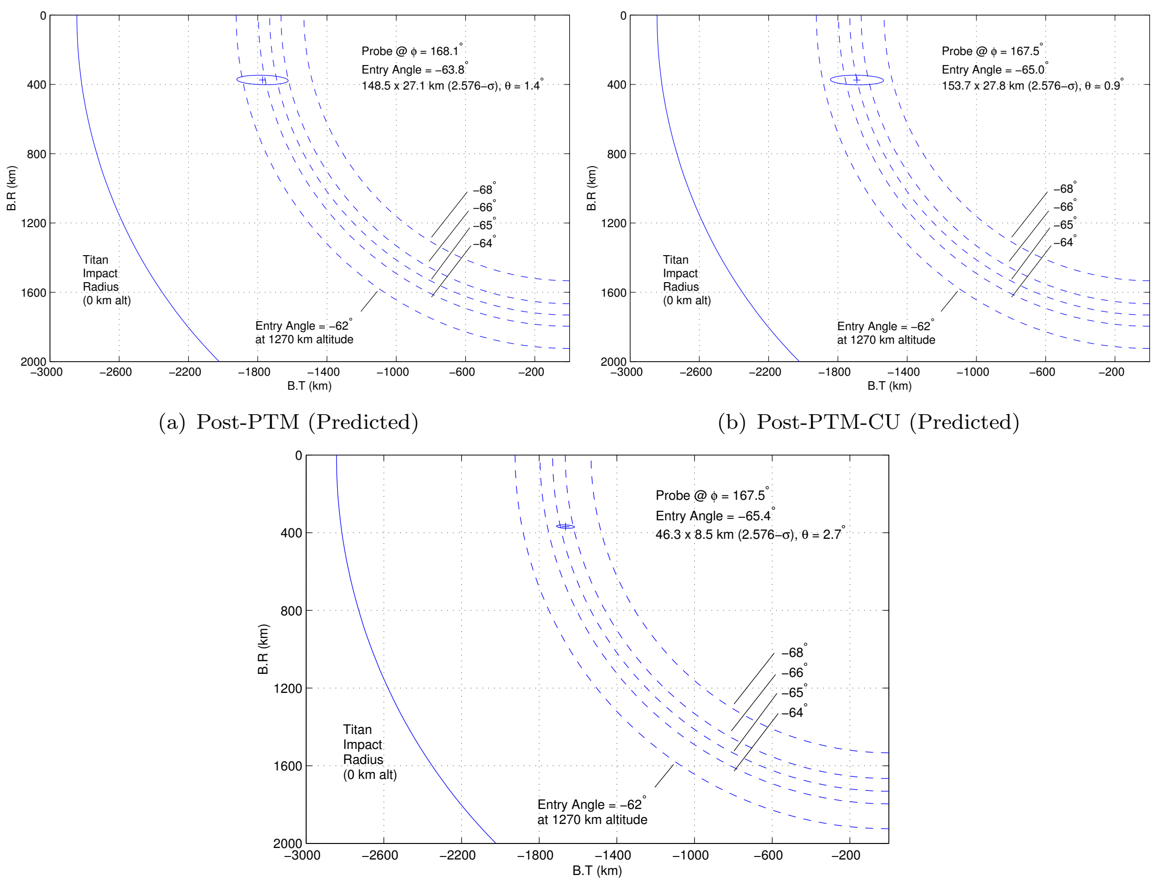
Titan-B to Titan-C Flyby: OTM-008, OTM-009, OTM-010, and OTM-010a

On 14-Jan-2005, the Huygens probe entered Titan's atmosphere and landed on its surface. The Cassini Navigation Team had two main goals during the Huygens probe mission. The first goal was to release the Huygens probe from the Cassini orbiter so that it would be delivered to Titan within certain target constraints. This was accomplished through the executions of OTM-008 and OTM-009, also known as the Probe Targeting Maneuver (PTM) and PTM cleanup (PTM-CU). At an interface altitude of 1270 km above Titan*, the probe was targeted to an entry angle of -65.0°, an angle of attack of 0°, and a B-plane angle of 167.5° at an interface time of 14-Jan-2005 09:07:00 ET-SCET. The second goal was not only to get the orbiter off an impacting trajectory after probe release, but also to position it for probe relay during the probe descent. This goal was satified by the executions of OTM-010 and OTM-010a, also referred to as the Orbiter Deflection Maneuver (ODM) and ODM cleanup (ODM-CU). OTM-010 and OTM-010a were targeted to the 60,000 km Titan-C (Tc) encounter. Besides designing these maneuvers, Navigation also analyzed the probe entry errors and the probe relay pointing uncertainties with each OD delivery and

*The interface altitude defined the point where JPL's responsibility for orbit propagation ended and the European Space Agency's (ESA) responsibility began.

maneuver design following the Titan-B (Tb) flyby until probe delivery. This was facilitated with the prior development of two special software tools: the Probe Entry Tool (developed by T. D. Goodson and S. V. Wagner) and the Probe Relay Pointing Tool (developed by J. B. Jones and S. V. Wagner). The Navigation team succeeded in meeting all requirements for the probe mission.[10,11]

OTM-008 (PTM) was a 12 m/s main engine burn performed on 17-Dec-2004. A week later on 23-Dec-2004, OTM-009 (PTM-CU) was executed on RCS thrusters. Probe separation (SEP) on 25-Dec-2004 released the Huygens probe from the spacecraft, with the probe following the trajectory established by OTM-009 and SEP. The requirements to be met by PTM and PTM-CU were a 99% entry-angle corridor of -65.0° ± 3° and a 3-σ angle-of-attack corridor of ±5° at the interface time.[12] If only PTM had been performed (i.e., no PTM-CU), the predicted probe 99% delivery dispersion would have violated the 99% entry-angle corridor requirement at the shallower end, as seen in Figure 4a. Therefore, PTM-CU was required. The calculated PTM-CU put the predicted probe 99% delivery dispersion well within the entry-angle corridor (Figure 4b), and the reconstructed trajectory (Figure 4c) verified that the entry-angle requirement was met.



(a) Post-PTM (Predicted)

(b) Post-PTM-CU (Predicted)

(c) Post-PTM-CU (Reconstructed)

Figure 4 Titan B-Plane Deliveries of Huygens Probe. *Delivery ellipses (99%) mapped to Titan B-plane in Titan True Equator-of-Date (EOD) coordinates at interface time. Entry-angle contours computed with respect to the Titan body-fixed reference frame.*

Table 5 lists the reconstructed entry angle and angle of attack values. The OD estimates were the best estimates determined by OD. The mean and %tile values were computed in a Monte Carlo simulation. The mean and OD estimate values match as expected. It can be seen that the entry angle and angle of attack were well within the requirements.

Table 5
RECONSTRUCTED PROBE ENTRY STATISTICS

Entry Angle (deg)	OD Estimate	99.5%	Mean	0.5%	1-σ
	-65.40	-66.08	-65.40	-64.71	0.27
Angle of Attack (deg)	OD Estimate	99%	Mean	1%	1-σ
	1.445	1.456	1.445	1.433	0.0048

Figure 5 presents the entry-angle statistics computed with each OD delivery and maneuver design. It can be observed that all the predictions following the PTM-CU design (23-Dec-2004) met the entry-angle requirements. Data in Table 5 and plots in Figures 4 and 5 were generated with the Probe Entry Tool.[13]

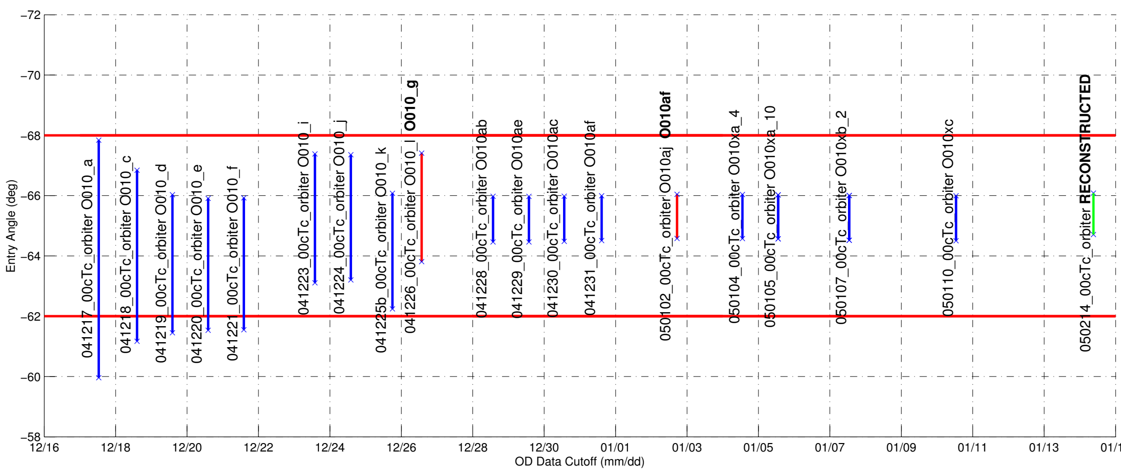
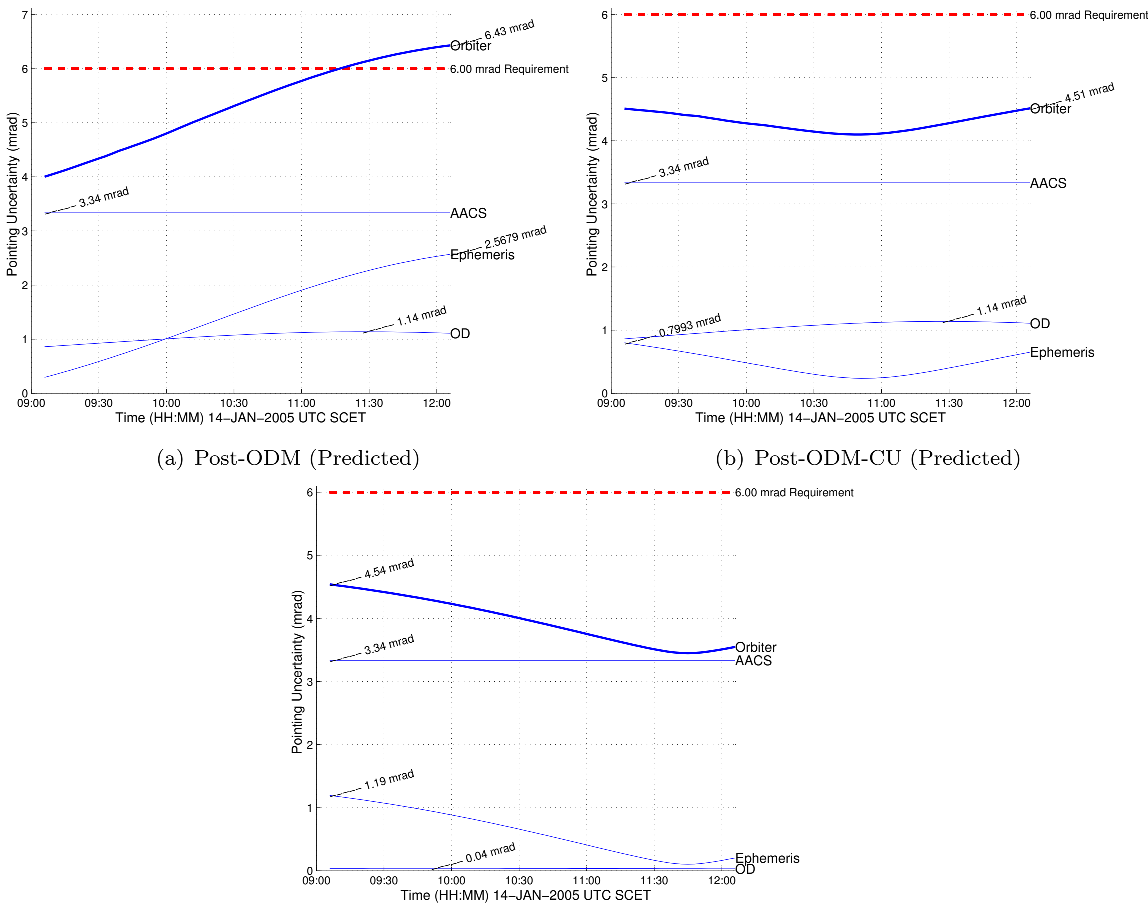


Figure 5 History of Entry-Angle Corridor Estimates. *Bars show extent of 99% entry-angle corridor. Labels denote OD delivery and maneuver design names. OD delivery after PTM-CU was 041223_00cTc and deliveries at ODM and ODM-CU were 041226_00cTc and 050102_00cTc. Reconstructed values (050214_00cTc) are shown only for comparison.*

OTM-010 (ODM) was a 24 m/s main engine burn executed on 28-Dec-2004. A week later on 3-Jan-2005, OTM-010a (ODM-CU) was performed on RCS thrusters. Besides meeting the Tc flyby conditions, ODM and ODM-CU had to meet certain probe relay pointing requirements during probe descent (from the nominal probe interface time of 14-Jan-2005 09:07:00 ET-SCET to three hours past). An orbiter pointing accuracy of 6 mrad (99%) during the probe relay timeframe was required, with an Attitude and Articulation Control Subsystem (AACS) allocation of 4 mrad (99%) and a Navigation allocation of 3 mrad (99%). The orbiter pointing uncertainty (99%) during probe relay was determined by several error sources: ephemeris, OD, and AACS*. It was computed in a Monte Carlo simulation with

*The AACS pointing error was comprised of inertial knowledge, deadbanding, and modelling errors.

only the ephemeris error added directly. Figure 6a shows that if only ODM had been performed (i.e., no ODM-CU), the orbiter pointing accuracy of 6 mrad would not have been achieved after two hours of the probe relay. Figure 6b reveals that the predicted post-ODM-CU probe relay pointing accuracy remained under the orbiter pointing requirement throughout the probe relay time frame. Thus, ODM-CU was performed to achieve the necessary pointing accuracy, as opposed to an update of the onboard pointing parameters. Finally, Figure 6c illustrates how the reconstructed probe relay pointing maintained the prescribed orbiter pointing accuracy of 6 mrad. Plots in Figure 6 were generated using the Probe Relay Pointing Tool.[14]



(a) Post-ODM (Predicted)

(b) Post-ODM-CU (Predicted)

(c) Post-ODM-CU (Reconstructed)

Figure 6 Orbiter Probe Relay Pointing Uncertainty (99%). *Probe relay data from interface time to 3 hours past. The red dashed line signifies the 6.00 mrad requirement on the orbiter pointing accuracy. The maximum values of each pointing component are labeled.*

Titan-C to Titan-3 Flyby: OTM-011, OTM-012, and OTM-013

Returning to the 3-maneuvers-per-flyby strategy, OTM-011, OTM-012, and OTM-013 were designed to bring Cassini back to the nominal tour by targeting to the Titan-3 (T3) encounter. Since the Titan-C (Tc) flyby was high at 60,000 km for the Huygens probe relay (see the previous section "Titan-B to Titan-C Flyby"), the Tc gravity assist could not provide the required ΔV for targeting Titan at the much lower altitude of 1577 km at

T3. As a result, both OTM-011 and OTM-012 were necessarily large. OTM-011 (Tc+2d) was a main engine burn executed just two days after the Tc flyby on 16-Jan-2005. It was designed in a single-leg optimization with OTM-012 to reduce the T3 flyby altitude. Chained two-impulse optimization was also considered in designing OTM-011 (i.e., OTM-011 designed with downstream maneuvers in later encounter arcs). However, since OTM-011 and OTM-012 were both large deterministic maneuvers, this approach did not significantly reduce the size of OTM-011 or any of the downstream maneuvers. With a deterministic ΔV of approximately 21 m/s, OTM-011 would have increased by 20-25 m/s per day if delayed. Because of this, OTM-011 was performed earlier than usual.[15] The OD data cutoff was also made six days before OTM-011 since more data would have not driven down the aimpoint dispersions, which were mainly due to execution errors. OTM-012 (Tc+apo) was a near-apoapsis maneuver performed on the main engine on 28-Jan-2005, with a large deterministic ΔV of over 19 m/s. Finally, OTM-013 (T3-3d) was executed on 12-Feb-2005 with RCS thrusters to achieve the T3 flyby conditions.

Titan-3 to Enceladus-2 Flyby: OTM-014 to OTM-025

Following the Titan-3 (T3) encounter, all maneuvers performed adhered to the same 3-maneuvers-per-flyby strategy and chained optimization technique. Hence, maneuvers OTM-014 to OTM-025 are treated in this section, covering the targeted encounters Enceladus-1 (E1), Titan-4 (T4), Titan-5 (T5), and Enceladus-2 (E2). Using the chained two-impulse optimization strategy, flyby cleanup maneuvers are designed by coupling the first two maneuvers in a leg (in this case, the cleanup and near-apoapsis maneuvers) across several encounters. Figure 7 gives a schematic of this optimization technique.[5,16]

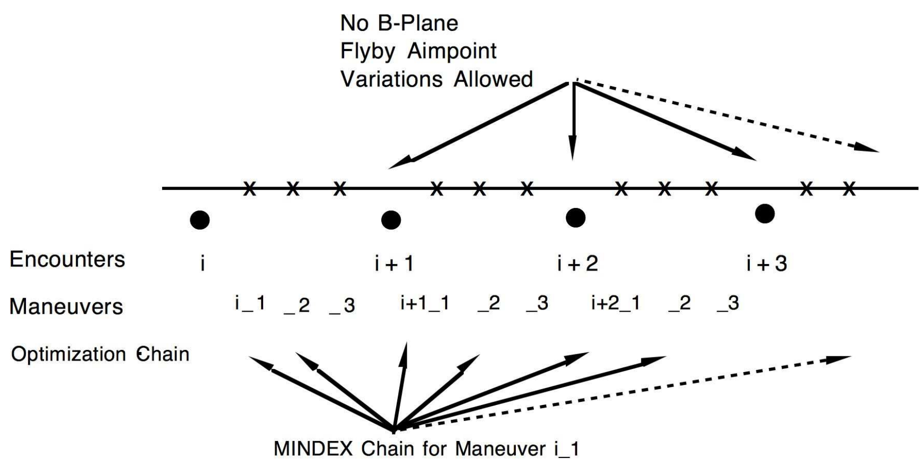


Figure 7 Chained Two-Impulse Optimization Strategy. *MINDEX refers to the LAMBIC[7] input variable name for the performance cost index.*

The first maneuver in each leg is computed by minimizing the following cost function (referred to as MINDEX in Figure 7):

$$J_i = \underbrace{||\Delta v_{i\_1}|| + ||\Delta v_{i\_2}||}_{leg\ i} + \underbrace{||\Delta v_{i+1\_1}|| + ||\Delta v_{i+1\_2}||}_{leg\ i+1} + \underbrace{||\Delta v_{i+2\_1}|| + ||\Delta v_{i+2\_2}||}_{leg\ i+2} + ... \quad (1)$$

$$= \sum_{m=0}^{n} ||\Delta v_{i+m\_1}|| + ||\Delta v_{i+m\_2}|| \quad (2)$$

subject to the constraints

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

$$\Delta(\mathbf{B}\cdot\mathbf{R})_{i+2} = 0,\ \Delta(\mathbf{B}\cdot\mathbf{T})_{i+2} = 0,\ \Delta TF_{i+2} = 0,\quad \textit{etc. up to } (i+m) \tag{3}$$

It follows that with N encounters, $2(N-1)$ maneuvers are being optimized ($6(N-1)$ parameters) and $3(N-1)$ constraints are made ($\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and TF). The remaining maneuvers in each leg are computed by the standard K-inverse strategy targeted to the nominal encounter aimpoints. Besides providing an optimal distribution of the ΔVs over multiple legs, this optimization strategy helps control asymptote errors without actively altering downstream flyby aimpoints after each encounter. Another benefit of this strategy is that the designed cleanup maneuver ΔVs are less sensitive to maneuver time shifts.[16]

OTM-014, OTM-017, and OTM-020 were all flyby cleanup maneuvers designed using the chained two-impulse optimization strategy. OTM-023 would have also been designed in this way, but it was cancelled. OTM-014 (T3+3d) was designed with a 3-encounter, 6-maneuver optimization chain (i.e., E1, T4, and T5 encounters; OTM-014, OTM-015, OTM-017, OTM-018, OTM-020, and OTM-021). Likewise, OTM-017 (E1+3d) and OTM-020 (T4+3d), were designed with 3-encounter, 6-maneuver optimization chains. Originally, OTM-014 and OTM-017 were intended to be implemented with 10-maneuver optimization chains (i.e., with 5 legs in Eqs. (1) and (2)), but the chains were shortened due to computational complexity. Around the time of the OTM-020 design, a low altitude Tethys flyby, dubbed the "Tethys tweak," was being added to the Saturn tour affecting several encounters downstream of E2.[17] Hence, a 6-maneuver optimization chain was used for the OTM-020 design since the design of the maneuvers farther downstream would change due to the reference trajectory update.

During the time period marked out by the targeted encounters from T3 to E2, a total of three maneuvers was cancelled: OTM-016, OTM-019, and OTM-023. The first of the cancelled maneuvers, OTM-016 (E1-3d), was the final approach maneuver to the first targeted Enceladus encounter, E1. Since the near-apoapsis maneuver OTM-015 (T3+apo) provided such an accurate delivery to Enceladus, OTM-016 became very small and consequently was cancelled. OTM-019 (T4-3d), also a final approach maneuver, was targeted to the T4 encounter. Again, the delivery to T4 was done excellently by the near-apoapsis maneuver, OTM-018 (E1+apo), negating the need for the final targeting maneuver to T4. Finally, OTM-023 (T5+3d) was the last maneuver that was cancelled in the first year of Saturn tour. Due to the great accuracy in the T5 delivery, this cleanup maneuver was deemed unnecessary and therefore cancelled.

With the exception of OTM-015, all the maneuvers performed from the T3 to the E2 encounter were within 1-σ of the predicted ΔVs. Of special note was the final approach maneuver to E2, OTM-025 (E2-5d). This maneuver was the smallest main engine burn performed to date at only 0.37 m/s. Incidentally, this maneuver was approximately the same size as OTM-004, which was performed on RCS and was the largest RCS maneuver performed to date.

EXECUTION ERROR MODEL

As described in the section "Maneuver Execution", the Gates model[6] is used to describe the spacecraft's maneuver execution errors. Significant savings in the predicted ΔV statistics for the remaining tour may be possible by updating this model. It may seem appropriate to just simply subtract the reconstructed from the expected ΔV (design ΔV plus associated ΔV events) to obtain the maneuver execution error, but this approach does not provide insight into the source of the error. Since each maneuver ΔV is in a different inertial direction yet is controlled by the spacecraft on-board accelerometer and attitude control system, body-fixed coordinates are the natural choice for analyzing the execution errors. A spacecraft coordinate frame already exists for Cassini (see section "Maneuver Execution"). However, a coordinate system with an axis parallel to the expected ΔV is preferred. The compromise is the thrust-vector-control (TVC) coordinate frame with Z_{TVC} parallel to the expected ΔV, X_{TVC} parallel to the projection of $X_{S/C}$ into the plane perpendicular to Z_{TVC}, and Y_{TVC} completing the right-handed system. The plane perpendicular to Z_{TVC} is referred to herein as the pointing plane.[2] With this type of coordinate frame, the maneuver execution error can be expressed with two perpendicular components, magnitude and pointing. Magnitude errors are computed simply by normalizing the vector differences of the reconstructed and expected ΔVs. Pointing errors are the vector differences of the reconstructed and expected ΔVs projected onto the pointing plane. They are given in X_{TVC} and Y_{TVC} components in m/s because they represent ΔV errors. Use of angular units is reserved for the proportional component of the pointing error.

Maximum Likelihood Estimator

The Gates model parameters are determined herein using maximum likelihood estimation.[2] First, the probability density function (pdf) for the magnitude error is

$$f_m(x) = \left[2\pi(\sigma_1^2 + y^2\sigma_2^2)\right]^{-1/2} \exp\left[-\frac{1}{2}\frac{(x-\mu_m)^2}{\sigma_1^2 + y^2\sigma_2^2}\right] \tag{4}$$

where x is the magnitude error, μ_m is the mean magnitude error, y is the magnitude of the maneuver, σ_1 and σ_2 are the fixed and proportional Gates model parameters for magnitude, and exp is the exponential function. Then, the likelihood is defined as the product of evaluations of $f_m(x)$ for each measurement:

$$L_m(\sigma_1, \sigma_2) = \prod_{i=1}^{N} f_m(x_i, y_i, \sigma_1, \sigma_2) \tag{5}$$

Likewise, for the pointing error, a two-dimensional vector, the pdf is

$$f_p(x) = \left[\sqrt{2}\pi(\sigma_3^2 + y^2\sigma_4^2)\right]^{-1} \exp\left[-\frac{1}{2}\frac{(x-\mu_p)^2}{\sigma_3^2 + y^2\sigma_4^2}\right] \tag{6}$$

where x is the length of the pointing error vector in units of speed, μ_p is the mean pointing error, y is the magnitude of the maneuver, and σ_3 and σ_4 are the fixed and proportional Gates model parameters for pointing. The likelihood is then defined as follows:

$$L_p(\sigma_3, \sigma_4) = \prod_{i=1}^{N} f_p(x_i, y_i, \sigma_3, \sigma_4) \tag{7}$$

A weighted maximum likelihood approach may be constructed by raising each term in the likelihood function to a power. For the magnitude errors, the exponent is the inverse of the 1-σ uncertainty. For pointing errors, the uncertainty is two-dimensional, so the inverse of the standard deviation of the error along the pointing direction is used. The Gates model parameters for magnitude errors are found by maximizing L_m; likewise for pointing errors L_p. Based on the form of these equations, only two measurements are required to determine the parameters. It follows then that with more measurements, more accurate estimates will be produced.

Preliminary Results

The Trajectory Correction Maneuvers (TCMs) from cruise to Saturn arrival and the OTMs covered in this paper were used in this analysis of the Gates model parameters. This included a total of 30 main engine maneuvers and 8 RCS maneuvers. TCM-1 was excluded from this study since it was executed with a different accelerometer scale factor and an error in the algorithm for estimating maneuver magnitude (see Ref. [1]). Table 6 lists all of the magnitude and pointing errors of OTMs covered in this paper (see Ref. [3] for the TCM magnitude and pointing errors).

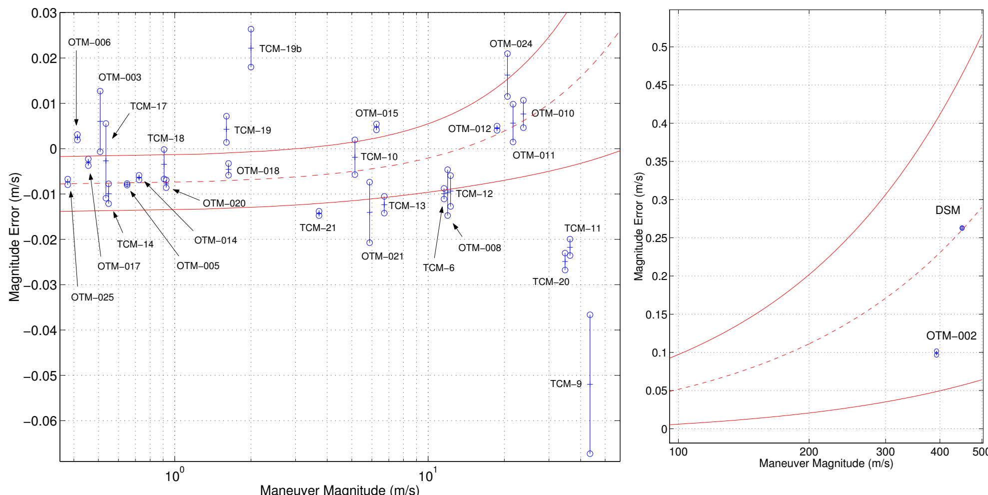
Table 6
MAGNITUDE AND POINTING ERRORS

	Magnitude			Pointing		
	Design ΔV +Events* (m/s)	Mag. Error (mm/s)	1-σ Mag. Uncert. (mm/s)	X_{TVC} Error (mm/s)	Y_{TVC} Error (mm/s)	1-σ Pointing Uncertainty† (mm/s)
OTM-002	392.96	99.14	2.73	455.73	-15.39	5.09 X 4.49, 69.3°
OTM-003	0.51	6.02	6.70	1.07	0.09	6.51 X 1.71, 92.0°
OTM-004	0.37	17.18	1.32	-5.47	-2.35	3.39 X 1.09, 63.7°
OTM-005	0.65	-7.87	0.17	-0.40	0.29	0.94 X 0.12, 91.2°
OTM-006	0.41	2.52	0.60	-1.70	3.92	1.41 X 0.51, 148.3°
OTM-008	11.94	-9.69	5.06	5.25	4.57	3.21 X 0.54, 172.8°
OTM-009	0.02	3.02	1.89	-0.21	-0.01	0.50 X 0.36, 89.5°
OTM-010	23.78	7.66	3.03	-62.96	-20.39	5.52 X 0.50, 91.9°
OTM-010a	0.13	4.04	2.23	2.65	0.55	3.32 X 1.20, 51.2°
OTM-011	21.64	5.64	4.18	-14.75	11.41	1.49 X 0.92, 165.1°
OTM-012	18.71	4.53	0.47	-23.99	4.45	1.09 X 0.87, 5.1°
OTM-013	0.21	1.82	0.83	0.93	0.03	1.94 X 0.45, 73.9°
OTM-014	0.72	-6.38	0.50	1.12	5.42	1.77 X 0.03, 90.6°
OTM-015	6.26	4.79	0.64	-1.75	6.81	0.38 X 0.05, 110.7°
OTM-017	0.46	-3.01	0.73	2.12	2.79	2.30 X 0.05, 82.9°
OTM-018	1.63	-4.56	1.29	1.97	-1.82	0.91 X 0.30, 0.2°
OTM-020	0.93	-7.76	0.85	2.00	4.88	0.89 X 0.11, 96.8°
OTM-021	5.88	-14.06	6.68	15.09	10.80	6.58 X 0.40, 30.0°
OTM-022	0.06	0.77	0.06	0.16	1.40	1.02 X 0.11, 96.7°
OTM-024	20.57	16.24	4.73	-6.51	18.66	3.97 X 0.12, 32.0°
OTM-025	0.38	-7.33	0.62	-0.33	1.65	8.08 X 0.18, 83.3°

*The ΔV magnitude includes the design ΔV (burn and turns) plus all ΔV events related to the maneuver (e.g., deadband tightening, Reaction Wheel Assembly (RWA) / RCS transitions, Earth/Sun pointing, etc.).

†1-σ pointing uncertainty numbers are 1-σ ellipse dimensions (semi-major axis X semi-minor axis) with orientation angle (relative to pointing plane X_{TVC} axis).

Figures 8a & 8b show magnitude error as a function of magnitude for all of the main engine burns since launch. The 1-σ magnitude errors of 21 out of 30 (70%) main engine maneuvers were within the 1-σ bounds ($\approx$68%), as expected for a normal distribution. TCM-9 and TCM-19b were the greatest outliers in the data. Since TCM-19b used a different burn cut-off algorithm for SOI testing (see Ref. [3]), this may account for the large overburn. Outliers will be further explored in a future report.

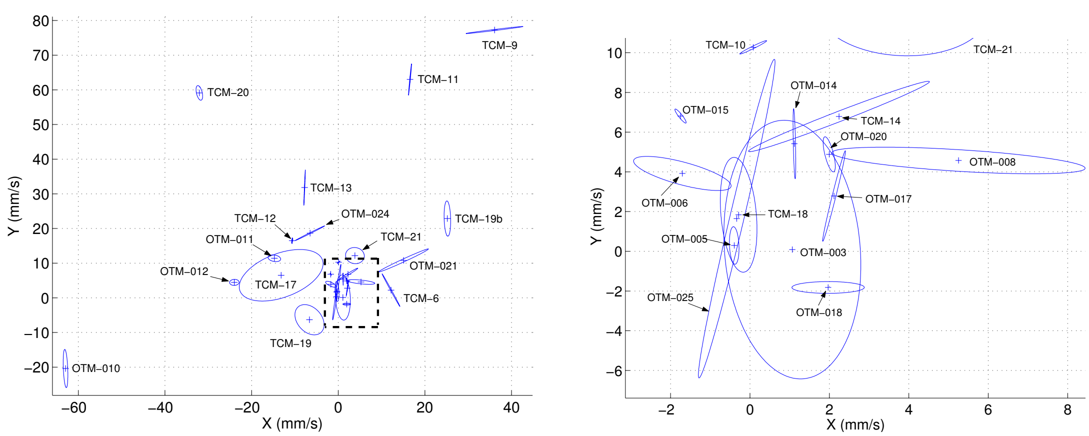


(a) Launch through OTM-025

(b) Deep Space Maneuver (DSM) and OTM-002

Figure 8 Main Engine Magnitude Error vs. Maneuver Magnitude. *Semi-log plots. Error bars show 1-σ uncertainties, dashed lines the magnitude biases, and solid lines the 1-σ bounds. Fixed and proportional magnitude bias values given in Table 9.*

The pointing errors in the pointing plane for most of the main engine maneuvers since launch are illustrated in Figures 9a and 9b. An initial glance of the error ellipses suggests a small bias in the positive Y direction and a small bias in the positive X direction. Future analysis will determine if such a conclusion can be supported.

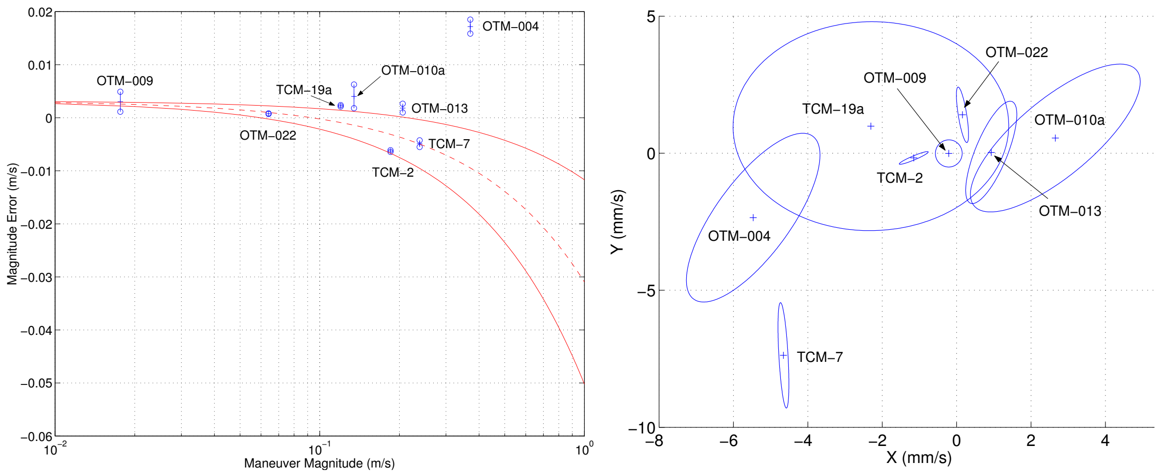


(a) Launch through OTM-025

(b) Close-up of Dashed Box in (a)

Figure 9 Main Engine 1-σ Pointing Error Ellipses in Pointing Plane. *DSM and OTM-002 are not shown since they are far from the origin.*

Figure 10a presents magnitude error as a function of maneuver magnitude for all RCS burns performed since launch. The 1-σ magnitude errors of 4 out of 8 (50%) RCS maneuvers were within the 1-σ bounds ($\approx$68%). Although not the expected distribution, it is not statistically meaningful due to the small number of RCS burns. TCM-2 and TCM-7 are notably the only "underburns." The pointing errors in the pointing plane of all the RCS maneuvers are displayed in Figure 10b. A preliminary look at the error ellipses suggests a bias of a few m/s in the negative X direction. Again, such biases will be investigated in a future analysis.



(a) Magnitude Error vs. Maneuver Magnitude

(b) 1-σ Pointing Error Ellipses in Pointing Plane

Figure 10 RCS Magnitude and Pointing Errors. *(a): Semi-log plot. Error bars show 1-σ uncertainties, dashed line the magnitude bias, and solid lines the 1-σ bounds. Fixed and proportional magnitude bias values given in Table 9. (b): 1-σ pointing ellipses shown.*

Model Comparisons

Tables 7 and 8 list the reported Gates execution error models for main engine and RCS. The January 2000 study (Ref. [2]) only analyzed the main engine burns since only two RCS burns were performed at that time. The currently implemented model from the Navigation Plan was known to be conservative when it was introduced. Finally, the preliminary results from the maneuvers performed to date are given for both main engine and RCS.

Table 7
MAIN ENGINE EXECUTION ERROR MODELS (1-σ)

		Jan. 2000 Study[2]	Aug. 2003 Navigation Plan[5]	Aug. 2005 Preliminary Study
Magnitude	Proportional (%)	0.03	0.2	0.05
	Fixed (mm/s)	1.8	10.0	6.0
Pointing (per axis)	Proportional (mrad)	0.55	3.5	1.0
	Fixed (mm/s)	2.0E-6	17.5	4.3

Table 8
RCS EXECUTION ERROR MODELS (1-σ)

		Aug. 2003 Navigation Plan[5]	Aug. 2005 Preliminary Study
Magnitude	Proportional (%)	2.0	1.9
	Fixed (mm/s)	3.5	8.3E-3
Pointing (per axis)	Proportional (mrad)	12.0	11.2
	Fixed (mm/s)	3.5	1.2

In this preliminary study, data was processed to remove magnitude and pointing biases from the error estimates. Table 9 shows the fixed and proportional components of the magnitude and pointing biases computed for both main engine and RCS maneuvers.

Table 9
EXECUTION ERROR BIASES

		Main Engine	RCS
Magnitude	Proportional (%)	0.06	-3.4
	Fixed (mm/s)	-8.0	3.2
Pointing (X_{TVC} axis)	Proportional (mrad)	0.3	-26.5
	Fixed (mm/s)	-1.4	1.9
Pointing (Y_{TVC} axis)	Proportional (mrad)	1.4	-12.6
	Fixed (mm/s)	1.3	1.0

CONCLUSIONS

In its first year of Saturn tour, the Cassini spacecraft has been navigated with amazing success. Delivery accuracy at each targeted encounter has been stellar and as a consequence, several maneuvers have been cancelled, saving ΔV. The Navigation team expects that with a better execution error model that even more ΔV can be saved throughout the mission. With three more years of the nominal Saturn tour remaining, the maneuver performance of the spacecraft will continue to be analyzed and reported. These efforts in turn will help extend the Cassini tour of Saturn.

ACKNOWLEDGMENTS

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The successful navigation for the Huygens probe mission was due in large part to the cooperation and great working relationship with the European Space Agency (ESA) team.

APPENDIX: B-PLANE DESCRIPTION

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "B-plane" coordinates[18] (see Figure 11). The B-plane is a plane passing through the target body 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 target body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target body 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 it 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** (i.e., $\mathbf{R} = \mathbf{S} \times \mathbf{T}$).

Trajectory errors in the B-plane are often characterized by a 1-σ dispersion ellipse, shown in Figure 11. 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 1-σ 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 1-σ distance error along the **S** direction, numerically equal to the time-of-flight error multiplied by the magnitude of the V_∞ vector.

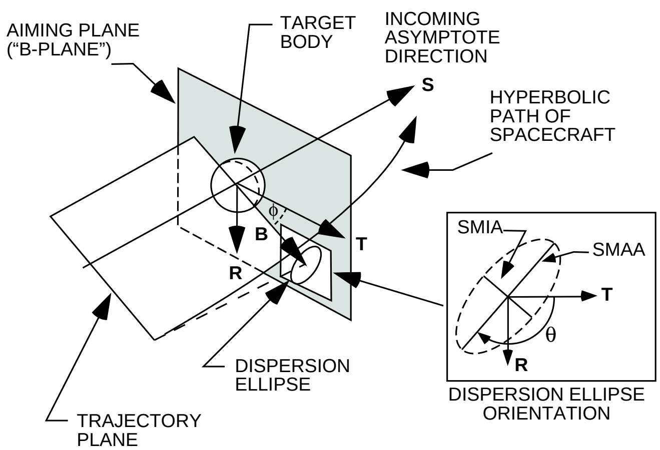

Figure 11 B-Plane Coordinate System

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