PREPARING FOR THE HUYGENS PROBE MISSION, CASSINI ORBIT DETERMINATION RESULTS FOR THE FIRST AND SECOND TARGETED TITAN ENCOUNTERS

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ABSTRACT

An orbit determination analysis of Cassini's trajectory including the first and second targeted Titan encounters has been generated and results are presented, continuing a series of orbit determination results throughout the Cassini mission[1,2,3,4,5]. These first two encounters helped set the stage for navigation of the Huygens probe mission, which took place during the third Titan encounter.

Dynamic modeling of the spacecraft and Saturn system, tracking data, including radio-metric and optical navigation data, and measurement modeling associated with the final trajectory analysis are described. Navigation predictions produced during the operational phase are compared with the final trajectory in order to gain insight into navigation performance and maneuver execution errors. Special attention is given to refinement of the dynamical environment of Saturn, particularly Titan, during the first two orbits.

SUMMARY (INTRODUCTION)

On Jan 14, 2005, the Huygens probe made history by landing on Titan, the largest moon of Saturn, after successfully descending through its hazy atmosphere. This historic event was the culmination of many engineering feats including accurately navigating the international Cassini/Huygens spacecraft to Titan. On October 26, 2004, near the end of its first orbit around Saturn, the Cassini spacecraft completed its first targeted flyby of Titan, designated Titan-a (Ta). Forty-eight days later, a second targeted encounter with Titan (Titan-b, Tb) was accomplished, setting the stage for the Huygens probe mission, which took place during the third Titan encounter (Titan-c, Tc). The Navigation Team faced many challenges preparing for Huygens' final descent into Titan's atmosphere. One considerable challenge was determining the dynamical environment of Saturn, including Saturn's gravity field and the orbits and masses of the major satellites, particularly Titan. The first two Titan flybys helped determine these quantities sufficiently to enable the probe mission navigation. A final orbit determination (OD) analysis, or reconstruction, was produced, and results of the analysis are presented here. The reconstruction included data from the apoapsis between Saturn orbit insertion (SOI) and the Titan-A flyby through a few days after the Titan-B flyby. Table Table 1 shows the significant events of this reconstruction. Figure Figure 1 shows the first two orbits of Cassini around Saturn, with major events labeled.

Table 1. Significant events.

Event	Date/Time (UTC)
Saturn Orbit Insertion	01-JUL-2004 01:12
Start of Data Arc	27-AUG-2004 15:30
OTM-3 (Peripasis Raise Maneuver Cleanup)	07-SEP-2004 16:30
OTM-4 (Ta – 3 days)	23-OCT-2004 06:16
Titan-A Flyby	26-OCT-2004 15:30
Saturn Periapse	28-OCT-2004 10:20
Iapetus Close Approach	17-OCT-2005 23:16
OTM-5 (Ta + 3 days)	29-OCT-2004 06:15
OTM-6 (Ta + apoapsis)	21-NOV-2004 05:00
Saturn Apoapse	21-NOV-2004 08:41
OTM-7 (Tb – 3 days, Cancelled)	10-DEC-2004 03:06
Titan-B Flyby	13-DEC-2004 11:38
Dione Flyby	15-DEC-2004 01:41
Saturn Periapse	15-DEC-2004 05:51
End of Data Arc	17-DEC-2004 00:00
Titan-C Flyby	14-JAN-2005 11:12

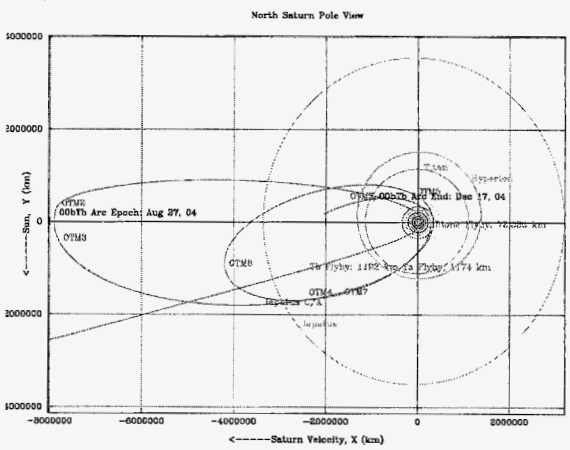

Figure 1. The first two orbits of Cassini.

All navigation reconstruction requirements, which include pointing and time of closest approach uncertainties, were met for this phase of the mission. The control errors (i.e. maneuver execution + OD errors) associated with the Ta flyby were greater than one-sigma, while the Tb control errors were about one-

quarter-sigma. All maneuver execution errors were sub-sigma except for the ΔV associated with OTM-4. The excellent performance of OTM-5 and OTM-6 allowed for the cancellation of OTM-7. The control errors associated with OTM-7 would have been significantly smaller than those of OTM-6, yielding a smaller control uncertainty, thus the Tb control sigma-errors are somewhat deflated.

The control errors were dominated by OD errors, mainly due to errors in the Titan ephemeris. As such, the prediction errors (i.e. OD errors only) were multi-sigma for both the Ta and Tb flybys. Both flybys were targeted to achieve a 1200 km altitude. The actual reconstructed altitude of the Ta closest approach was 1174 km and occurred approximately four seconds later than targeted. The reconstructed altitude of the Tb closest approach was 1192 km and occurred approximately 2.5 seconds later than targeted. Table 2 shows the Ta and Tb control and OD errors and associated sigma-error, which is the error divided by the formal, one-sigma uncertainties of the maneuver and/or OD predictions.

Table 2. Titan-a and Titan-b prediction errors.

Case	B.T (km)	B.R (km)	Alt (km)	TCA (s)	3-D (km)	3-D (σ)*
Ta Control	32.0	5.6	25.9	4.21	40.3	4.9
Ta OD	39.0	11.0	29.2	2.27	42.5	4.7
Tb Control	17.0	5.5	7.7	2.44	22.5	0.3
Tb OD	3.3	4.2	5.4	0.22	5.5	3.0

*σ-Error = 3-D σ-error compared to formal 1-σ uncertainty

TRACKING DATA

The following briefly describes the tracking data that was used in the 00bTb reconstruction. A more detailed description of the tracking data that is used in the general Cassini OD process can be found in [Antreasian, 2005].

Radio Metric Data

X-band Doppler and range data from August 27, 2004 to December 16, 2004 were used for this reconstruction. The Doppler data was 2-way coherent Doppler and was collected approximately once per day. The Doppler data was weighted on a per-pass basis to the standard deviation multiplied by a scale factor of 3.36. No 1- or 3-way Doppler data was used in this reconstruction. The ranging data was collected concurrently with the 2-way Doppler data and was weighted with the same algorithm. Normalized (i.e. post-fit residual divided by the weights) data residuals are shown in Figure 2.

Optical Navigation Data

Optical navigation (opnav) data was collected from August 27, 2004 to December 13, 2004. The distribution of satellites imaged is shown in Table 3. There were no Phoebe images taken during this data arc. Each opnav includes background stars to help estimate the camera pointing.

Table 3. Number of opnav pictures acquired.

Satellite	Number	Satellite	Number
1: Mimas	54	5: Rhea	56
2: Enceladus	48	6: Titan	52
3: Tethys	43	7: Hyperion	41
4: Dione	58	8: Iapetus	48

The opnav data were weighted based on the characteristics of the target satellite as well as the distance between Cassini and the satellite. The optical data residuals are also shown in Figure 2. The numbers in the plot correspond to the satellite number shown in Table 3. The plot indicates that some of the opnav images were over-weighted as compared to their post-fit residuals, particularly Enceladus.

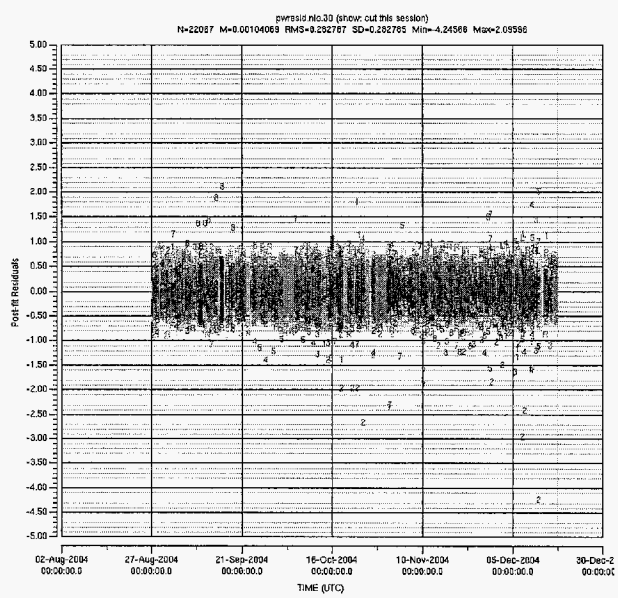

Figure 2: Post-Fit Data Residuals (Normalized)

DYNAMIC MODELING AND PARAMETER ESTIMATION

Various parameters were estimated to adjust the spacecraft model, the planetary and satellite model, and the measurement model. These parameters may be estimated as a bias value constant over the entire arc or a stochastic set of values that change over time. If not estimated, a parameter may be "considered" to allow for uncertainties in the variable to be included in the estimation process. In all, X parameters were estimated and Y parameters were considered in the 00bTb

reconstruction solution. All uncertainties given below are formal, 1-σ uncertainties.

Spacecraft Models

The spacecraft models include several elements. The initial state at August 27, 2004 09:00 ET was taken from a previous operational OD solution. The Cartesian position and velocity were estimated using an a priori covariance equal to five times the formal post-fit covariance from the previous OD solution. The corresponding position and velocity uncertainties are 145 km and 352 mm/s, respectively. The thermal radiation was modeled as an exponentially decaying acceleration with an estimated bias parameter in each of the spacecraft axes. The a priori values used were taken from the reconstruction from the Jupiter to Saturn reconstruction arc [Roth, 2005]. The uncertainties were 10% in spacecraft Z-axis and 50% in X- and Y-axes. The force due to solar pressure was included with nominal reflectivity values but no parameters were estimated. Four Orbit Trim Maneuvers (OTM) were executed and estimated with the following parameters: ΔV, right ascension, declination, start time, and in one case, thrust. Maneuver estimates are discussed more thoroughly in the following section.

The ΔV associated with each reaction control system, RCS, thruster event was modeled using predictions provided by the attitude articulation and control subsystem (AACS) team. Most of the RCS events were modeled as an impulsive ΔV for which the magnitude was estimated with an a priori uncertainty of 5 mm/s.. The RCS thrusting during the Ta flyby was modeled using an acceleration model since significant thrusting was sustained over a long period of time (discussed in more detail below).

To account for any force mis-modeling, a set of stochastic non-gravitational accelerations were estimated in spacecraft fixed axes with an uncertainty of 1.426×10^{-12} km/s^2. During some events, when the spacecraft was controlled using the RCS thrusters (as opposed to the reaction wheels), the stochastic acceleration model was given an order of magnitude larger uncertainty in the spacecraft-Z component (along the thrust direction) to account for deadband thrusting.

Planetary and Satellite Models

The satellite and planetary model used for the reconstructed trajectory was the JPL ephemeris, sat188. This ephemeris was developed using Voyager and Pioneer 11 spacecraft radio and optical tracking data, US Naval Observatory, Hubble, and Table Mountain astrometric observations as well as numerous historical observations dating back to the 1960s, in addition to Cassini radio and optical tracking data through November 19, 2004. The a priori satellite/planet correlated covariance was taken from sat188 with data after August 27, 2004 removed. The satellite model includes the estimation of the mass, initial position, and initial velocity of Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, and Iapetus on January 2, 2004. The Saturn ephemeris was also estimated, as well as the Saturn barycenter mass, J2, J4, and the pole orientation.

Measurement Models

The radiometric measurement models include many estimated and considered parameters. The station locations (2-3 cm), troposphere (1.0 cm), ionosphere (15 cm day, 4 cm night), and earth orientation (2 cm/axis) uncertainties were all considered (with the indicated uncertainty). A per-station and per-pass ranging bias was estimated with uncertainties of 1 m and 3 m, respectively. The optical measurements were adjusted by estimating pointing corrections for each picture with an uncertainty of 1 degree per axis. The Titan pictures also included an estimate of the 0th and 1st order phase bias with a 5% uncertainty.

Flyby Modeling

Figure 3 shows the magnitude of the accelerations that were acting on the spacecraft during the Ta flyby. During the flyby, Titan's gravitational force grew to more than an order of magnitude larger than Saturn's gravitational force, which were by far the largest forces acting on the spacecraft. Figure 3 also demonstrates the considerable effect of the thrusting, which was modeled as a variable, time-averaged acceleration over the time period of the thrusting events. The thrust model was developed using telemetry that is derived from an on-board calculation of thruster ΔV based on thruster on-times and various spacecraft and thruster parameters. The total ΔV imparted by thrusting during the Ta flyby was in excess of 600 mm/s, which, as shown, is the largest force acting on the spacecraft other than the Titan and Saturn point mass gravitational forces. There was about an order of magnitude less thrusting during the Tb flyby, which allowed for the thrusting to be estimated as discrete impulsive ΔVs.

The acceleration due to thrusting was not estimated, but rather a relatively loose (compared to nominal operations) stochastic acceleration model was estimated to compensate for thruster mis-modeling. The apriori uncertainty of the stochastic acceleration was increased to 1.426×10^{-9}, 7.124×10^{-10}, and 7.124×10^{-10} in the spacecraft Z, X, and Y axes during the periods of heavy thrusting on the inbound and outbound legs. During the flyby itself, there was significantly less thrusting, thus the uncertainties were set an order of magnitude smaller than the above values. Figure 4 shows both the apriori

uncertainty and estimated value of the stochastic acceleration.

Near periapse, Titan's J2 and drag effects become significant. However, these effects were poorly observed by the radio tracking data, which had a 32-hour gap surrounding the flyby since the spacecraft was pointed away from Earth collecting science data. Attempts to estimate the drag and J2 parameters were unsuccessful and the effect of these forces on the spacecraft trajectory were overpowered by other estimated parameters. Due to the large uncertainty associated with the current models of J2 and drag, and the reasons mentioned above, these effects were not included in the force model. The J2 acceleration shown in Figure 3 represents a reasonable approximate based on geophysical shape assumptions of Titan. The drag acceleration was studied using the Titan-5 flyby in April, 2005 (ref. DragMemo), and the acceleration shown is consistent with that study.

Other significant forces include solar gravity and Saturn's J2 effect.

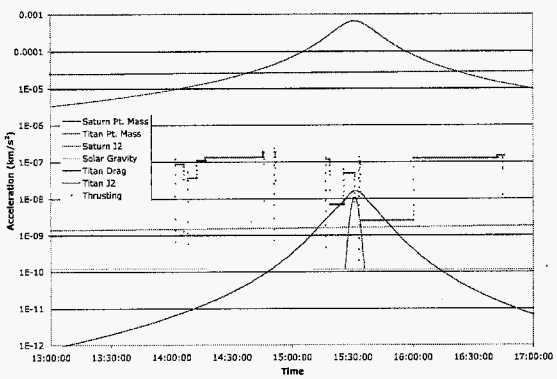

Figure 3. Accelerations acting on Cassini during the Titan-a flyby.

MANEUVER RECONSTRUCTION

As shown in Table 1, there were five maneuvers planned within the data arc. A more detailed discussion of the maneuver design process can be found in Wagner, 2005. However, this section presents the results of the maneuver estimates obtained through the OD process as compared with the maneuver designs and a priori uncertainties.

OTM-3 and OTM-4 were necessary in order to clean up the execution errors of OTM-2 (periapse raise maneuver). Both maneuvers targeted the 1200 km Ta flyby. OTM-3 was executed approximately 15 days after OTM-2. OTM-4 was executed approximately three days before the Ta flyby. OTM-5 and OTM-6 were designed using a two-maneuver optimization scheme. Their purpose was to clean up the errors associated with the Ta flyby and target the Tb flyby.

The Tb flyby altitude was originally planned to be 2200 km, however the trajectory was redesigned in order to prevent the Iapetus flyby in late December from causing unacceptable uncertainties in the probe's targeted entry conditions [Bordi, 2005]. The redesign decreased the Tb flyby altitude to 1200 km and approximately doubled the Iapetus flyby distance, mitigating the effect of the Iapetus mass uncertainty on the probe's flight path angle.

OTM-5 was executed approximately three days after the Ta flyby. OTM-6 was executed approximately 23 days later near Saturn apoapse. OTM-7, which would have re-targeted the Tb flyby, was scheduled approximately 3 days before the Tb flyby in order to clean up any errors associated with OTM-6. Due to the excellent performance of OTM-6, OTM-7 was cancelled.

The second maneuver, OTM-4, was executed using the monopropellant RCS thrusters. The other three maneuvers were executed using the 440 N bipropellant thruster of the main engine, and were performed in blow-down mode. The first two maneuvers, OTM-3 and OTM-4 were also estimated in the 00aTa reconstruction arc [Roundhill, 2005] allowing for a comparison between the two results. Reconstructed results for the other maneuvers, OTM-5 and OTM-6, were only contained in the 00bTb reconstruction arc.

Designed and estimated maneuver values and one-sigma uncertainties are presented in Table 4-Table 7, where right ascension and declination are listed in the Earth mean equator of 2000 (EME2000) coordinate frame. Smaller uncertainties in the current reconstruction solution result primarily from using tracking data through the Tb flyby. The larger uncertainties of ΔV and thrust associated with OTM-4 are a result of estimating the start time in the current reconstruction.

Table 4. OTM-3, PRM C/U (Sep.7, 2004 16:30 UTC) nominal and reconstructed values.

Case	RA (°)	Dec(°)	ΔV (mm/s)
Design	183.39±7.24	-73.68±2.03	506.54±10.05
00aTa	183.32±1.47	-73.93±0.65	511.67± 6.66
00bTb	183.89±1.44	-73.70±0.63	512.94± 6.41

Table 5. OTM-4, Ta-3 (Oct. 23, 2004, 06:16 UTC) nominal and reconstructed values.

Case	RA(°)	Dec (°)	ΔV (mm/s)
Design	80.19±0.98	26.43±0.87	372.27±8.23
00aTa	79.88±0.36	26.66±0.66	385.04±1.61
00bTb	79.35±0.30	26.79±0.46	383.38±4.39

Table 6. OTM-5, Ta+3 (Oct. 29, 2004 06:15 UTC) nominal and reconstructed values.

	RA(°)	Dec(°)	ΔV (mm/s)
Design	160.09±1.59	-8.35±1.57	654.61±10.08
00bTb	160.16±0.05	-8.37±0.07	646.35±0.17

Table 7. OTM-6, Ta+Apo (Nov. 21, 2004 05:00 UTC) Nominal and Reconstructed Values.

	RA(°)	Dec(°)	ΔV (mm/s)
Design	140.90±2.46	1.16±2.46	419.56±10.03
00bTb	141.41±0.25	1.41±0.14	420.47±0.96

TITAN-A AND TITAN-B FLYBY RESULTS

Cassini performed the first of its 45 planned prime mission targeted flybys of Titan on October 26, 2004. As mentioned previously, OTM-3 and OTM-4 targeted the 1200 km flyby of Ta on October 26 at 15:30:09 UTC. These resulted in an actual closest approach of 1174 km at 15:30:05 UTC. Figure 4 shows the B-plane plot of the pre-OTM-3 OD solution, the OTM-3 maneuver design, and the pre-OTM-4 OD solution, which provide insight into the effect and accuracy of OTM-3 as mapped to the Ta B-plane. The B-plane coordinate system axes are centered on Titan with the T-axis parallel to the Earth Mean Orbital Plane at the J2000 epoch. The ellipses shown for each case represent its one-sigma uncertainty. Table 8 lists the time of closest approach (TCA) and associated one-sigma uncertainties of the solutions shown in Figure 4. The pre-OTM-4 OD delivery shown demonstrates that OTM-3 performed within its one-sigma delivery dispersions in the B-plane and TCA.

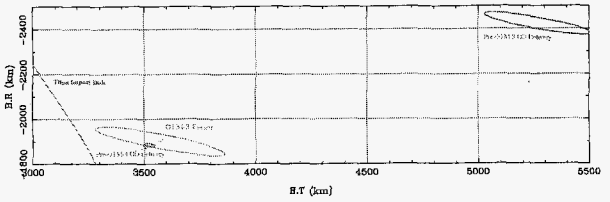

Figure 4. OTM-3 maneuver design and performance for Titan-a B-plane targeting.

Table 8. OTM-3 Maneuver Design and Performance for Titan-a TCA targeting (on October 26, 2004).

Case	TCA
Pre-OTM-3 OD Delivery	15:25:52.70±39.28
OTM-3 Design	15:30:08.82±50.07
Pre-OTM-4 OD Delivery	15:30:28.28±00.78

Figure 5 shows the B-plane plot of the pre-OTM-4 OD solution, the OTM-4 maneuver design, the pre-Ta OD solution, and the reconstructed solution. Table 9 lists the TCA and uncertainties of the solutions shown in Figure 5

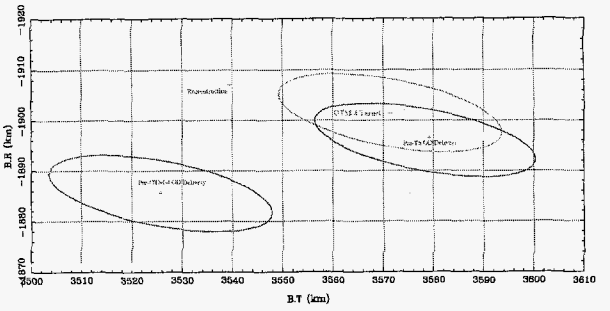

Figure 5. OTM-4 maneuver design and performance for Titan-a B-plane targeting.

Table 9. OTM-4 Maneuver Design and Performance for Titan-a TCA targeting (on October 26, 2004).

Case	TCA
PreOTM4 OD Delivery	15:30:28.28±0.78
OTM04 Design	15:30:08.82±0.87
Pre-Ta OD Delivery	15:30:06.88±0.57
00bTb Reconstruction	15:30:04.61±0.06

As shown in Figure 5 and Table 9 (and also Table 2), the actual Ta flyby did not fall within the one-sigma control dispersions. The OTM-4 control error was approximately two-sigma in the B-plane and altitude and five-sigma in TCA. The final OD delivery before the Ta flyby had errors of approximately two-sigma in the B-plane and altitude and four-sigma in TCA. Most of this error was caused by errors in the Titan ephemeris. Until the Ta flyby, Titan's ephemeris estimation was primarily driven by optical navigation data. However, radio data immediately before and after the Ta flyby provided a much more accurate estimate of the ephemeris. The post-Ta radio data caused a shift of approximately 40 km in the along-track direction and 5 km in the orbit-normal direction. The Titan GM also shifted by approximately one-sigma from 8978.046 ± 0.089 to 8978.163 ± 0.063 km^3/s^2. The reason for the miss is discussed in more detail in the next section.

Cassini performed the second targeted flyby of Titan on December 13, 2004. As mentioned previously, OTM-5 and OTM-6 were designed using a two-maneuver optimization scheme and targeted the 1200 km flyby of Tb on December 13 at 11:38:13 UTC. These resulted in an actual closest approach of 1192 km at 11:38:15 UTC. Figure 6 shows the B-plane plot of the OTM-5 maneuver design, the pre-OTM-6 OD solution, and the combined final Tb target. The pre-OTM-5 OD solution was not included in Figure 6 due to scale. Table 10 lists the TCA and associated one-sigma uncertainties for the solutions shown in Figure 6. These results show that OTM-5 performed within its one-sigma dispersions in the B-plane and TCA. Note that the OTM-5 target did not match the final Tb target because of the two-maneuver optimization.

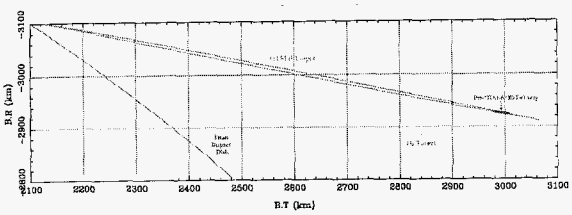

Figure 6. OTM-5 maneuver design and performance for Titan-b B-plane targeting.

Table 10. OTM-5 Maneuver Design and Performance for Titan-b TCA targeting (on December 13, 2004).

Case	TCA
Pre-Ta OD Delivery	11:45:00.62±89:57.17
Pre-OTM-5 OD Delivery	10:39:53.65±00:21.47
OTM-5 Design	11:40:31.79±01:08.33
Pre-OTM-6 OD Delivery	11:39:37.03±00:04.39
Tb Target	11:38:12.82±00:00.00

Figure 7 shows the B-plane plot of the pre-OTM-6 OD delivery, the OTM-6 maneuver design, the pre-Tb OD delivery (which was used for the Dione pointing live update), and the reconstruction solution. Table 11 lists the TCA and uncertainties for the solutions shown in Figure 7.

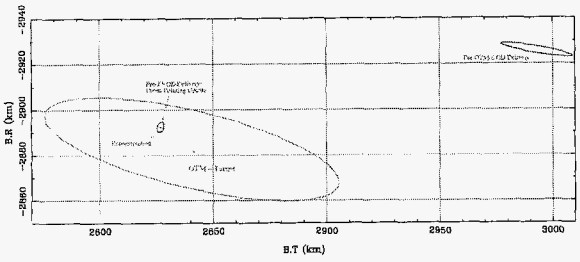

Figure 7. OTM-6 maneuver design and performance for Titan-b B-plane targeting.

Table 11. OTM-6 Maneuver Design and Performance for Titan-b TCA targeting (on December 13, 2004).

Case	TCA
PreOTM6 OD Delivery	11:38:97.03±4.39
OTM-6 Design	11:38:12.82±11.7
Pre-Tb OD Delivery	11:38:15.04±0.26
Reconstruction	11:38:15.25±0.06

Figure 7 and Table 11 (and also Table 2) show that OTM-6 performed within its one-sigma control dispersions in the B-plane, altitude, and TCA, but that the OD delivery used in the Dione pointing update contained a two-sigma error in the B-plane and alitude and a one-sigma error in TCA. This error was again caused by a shift in the Titan ephemeris. The shift from the Tb flyby was approximately 3 km in the along-track direction and 2 km in the radial direction. Titan's GM again increased by about one-sigma from 8978.181 ± 0.061 to 8978.252 ± 0.033 km^3/s^2. The reason for the miss is discussed in more detail in the next section.

POST-FLYBY ANALYSIS

[Roundhill, 2005] described the effects of different modeling assumptions on the OD solutions during the Ta approach. These variations are used as a way of determining if there is a significant problem with the solution. The variations considered were the following:

- Thermal and stochastic accelerations
- Different arc epochs
- Varying data sets and weights
    - Tight/Loose
    - No F2, SRA, or opnava
    - Exclude satellite sets
- Scaling a priori satellite covariance

The results showed that solutions are generally consistent with one another, with the most important variations being, arc epoch, inclusion of opnavs, and scaling of satellite covariance.

As the Ta and Tb encounters approached we speculated that our predictions could contain multi-sigma errors, however based on extensive analysis of different model, filter, and data assumptions, what we thought was the best solution in each case was used. The uncertainties associated with these solutions did not account for unmodeled effects, thus multi-sigma shifts in the solution were somewhat anticipated after each Titan flyby. The overall goal of the orbit determination team was to provide the best possible mean trajectory in order to provide the science team with accurate predictions. Realistic uncertainties were a secondary objective, but were not artificially increased at the expense of an accurate trajectory prediction. An example of the tradeoff between an accurate trajectory prediction and uncertainty scaling, is the scaling of the a priori satellite ephemeris uncertainties. By scaling the uncertainties up, the uncertainties at the Tb encounter were increated as well, however the predicted flyby conditions drifted away from what turned out to be the actual flyby that was achieved. Thus, although the uncertainties grew, and thus better represented the true uncertainties, the trajectory prediction was degraded.

Post-encounter analysis was performed in order to determine the modeling errors that were present in the operational OD predictions of the Tb flyby. Several factors contributed to the multi-sigma prediction errors for both the Ta and Tb flybys. Figure Figure 8 shows the B-plane predictions of several OD modeling variations that were applied to the final OD solution prior to the Tb flyby, along with the post-flyby result. Included in the plot are the inclusion of Hyperion's GM as an estimated parameter, the modeling of the Ta flyby

thrusting using a varying acceleration, tightening the uncertainty of the stochastic acceleration parameters, updating the satellite model to a the most current model, and the most current satellite model with tight stochastic uncertainties. As can be seen, each of these variations improves the flyby prediction.

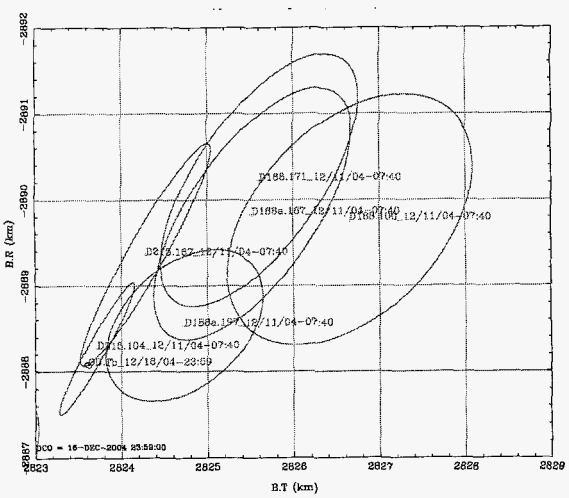

Figure 8 Titan-b B-Plane Predictions With Improved Model Assumptions

Titan is in a 3:4 mean longitude resonance with Hyperion, and thus Titan's ephemeris is effected by Hyperion's GM. During operations prior to the Tb flyby, Hyperion's mass was not estimated (it was included in the filter as a consider parameter) because it was thought to be unobservable by the data due to the uncertainties of the Saturnian system. This was certainly true before the Ta flyby, at which point attempts to estimate Hyperion's mass often resulted in negative values. After Ta, an estimation of Hyperion's GM was again attempted. This estimation resulted in a positive value, but the estimated mass resulted in a density that was lower than scientific models deemed plausible, and thus the estimate was ruled out. After the Tb flyby, Titan's ephemeris uncertainty was again reduced, and estimation of Hyperion's mass resulted in an even lower value, however the uncertainties were also dramatically reduced. After the Tb encounter, the new estimate of Hyperion's GM produced a much more stable set of solutions than those using the previous value. Since that time, with the inclusion of several more Titan flybys, the estimate of Hyperion's mass has not changed significantly, and we have a good deal of confidence in it's value. This inferred mass estimate will be validated during an upcoming close flyby of Hyperion in late September. Figure Figure 9 shows the significant effect of Hyperion's GM on Titan's ephemeris. The reference in the plots is the sat188 Titan ephemeris. The two plots shown are the changes in Titan's ephemeris when 1) Hyperion's GM is reduced from the sat188 value (0.57 km^3/s^2) to it's currently estimated value from sat215 (0.37 km^3/s^2), and 2) Hyperion's mass is set to zero.

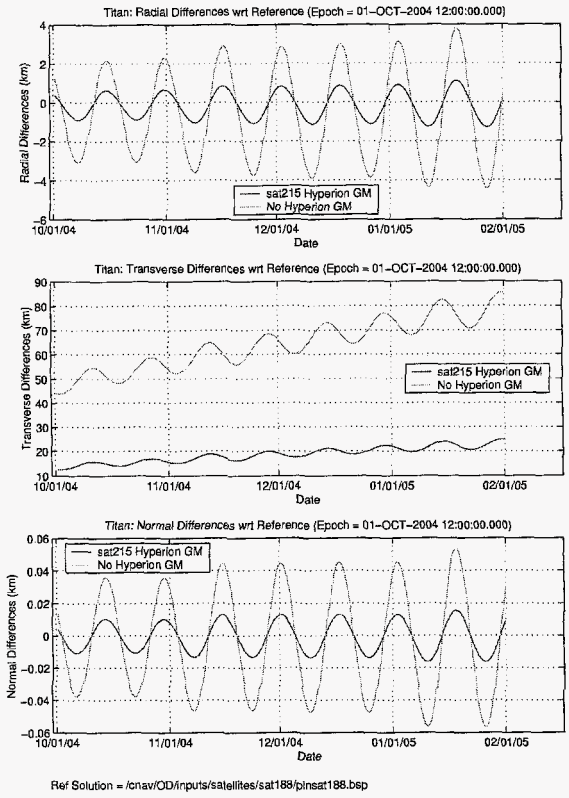

Figure 9 Hyperion's GM Effect on Titan's Ephemeris

During the recent, post-encounter analysis of the final OD solution prior to the Tb encounter the gravitation parameter, GM, of Hyperion was estimated. The solution causes a shift primarily to the left in the B-plane, which was not seen in any of the pre-encounter variation solutions, and was thus a significant contributor to the prediction error. Figure Figure 10 shows a mapping of Hyperion's GM and one-sigma uncertainty throughout an arc that contains both the Ta and Tb flybys. The mappings are produced using the reconstructed trajectory solution, which utilizes the sat188 satellite ephemeris model, as described previously, which includes data after the Ta flyby. Because of this it does not represent the GM estimates that were produced in real time, but rather give insight into the observability of Hyperion's GM as more data is included. As can be seen, data surrounding the Ta and Tb flyby contain powerful observations of Hyperion's GM. The a priori uncertainty of 0.1 km^3/s^2 was reduced to 0.06 km^3/s^2 after the Ta flyby, and was reduced by an order of magnitude to approximately 0.06 km^3/s^2 after the Tb flyby.

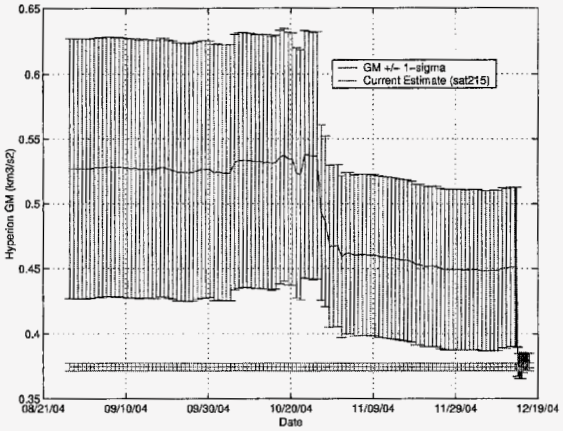

Figure 10: Hyperion's GM Estimate vs. DCO

Another modeling variation that was investigated during post-encounter analysis involved the modeling of the thrusting that occurred during the Ta flyby. More than 600 mm/s of thrusting was experienced during the flyby, which was poorly observed by the tracking data. Any errors in the thruster model were easily masked by other parameters, such as the Titan ephemeris or GM. The model used during operations broke the thrusting up into several impulsive DV events. The post-encounter analysis incorporated an acceleration model that more accurately modeled the continuous nature of the thrusting. This change caused a slight downward movement in the Tb prediction, but more importantly, cause a significant shift later in time of closest approach, yielding a value much closer to the post-flyby result. This shift in TCA was not seen in any pre-encounter variation solutions.

During the first few orbits of Saturn, the stochastic uncertainties were set conservatively high in order to account for dynamic mismodeling that we suspected was present in our OD analysis. It was later determined that this conservatism was actually degrading the operational solutions. During posts-encounter analysis of the final pre-flyby OD solution, the stochastic uncertainties were reduced by a factor of three. This caused a significant improvement in the Tb flyby prediction. This is another example of how over-inflating uncertainties can cause a significant degradation in the prediction performance.

The remainder of the error is due to errors in the satellite ephemeris model that could not be observed using the existing data set at the time. Updating the final pre-Tb OD solution with the most current satellite model, which includes Cassini data through August 13, 2005, improves the Tb flyby prediction to very close to the actual post-flyby results.

SATURN SYSTEM IMPROVEMENT AND UNCERTAINTY REDUCTION

Most of the parameters associated with the Saturnian dynamican system were improved, and associated uncertainties were dramatically reduced, during Saturn approach and first two orbits of Saturn. This improvement set the stage for the precise orbit determination that was necessary to successfully navigate the Huygen's probe mission. Of particular importance were the improvements in Iapetus' GM and Titan's ephemeris, especially considering that the Ta, Tb, and Tc flyby all occurred at the same longitudinal position in Titan's orbit. The orbit determination results from the probe mission are shown in Bordi, 2005.

Figure 11 shows the evolution of Titan's ephemeris with the addition of data. The reference in the plot is the most current satellite model, sat215, which includes all of the data described in sat188, plus Cassini data through August 13, 2005, which includes six close Titan flybys. Shown on the graph are the difference between sat215 and the following cases: Pre-Cassini, which does not include any Cassini data; Post-SOI, which is the reconstructed solution including data through SOI; Post-Ta, Post-Tb, and Post-Tc, which include data through the Ta, Tb, and Tc flyby's respectively. As can be seen, the addition of optical navigation images before SOI improved the ephemeris estimate slightly. However, the most significant improvements were obtained using the radio data that were collected near the Ta and Tb flybys. The Ta flyby resulted in a significant improvement in the transverse and radial components. The Tb flyby resulted in further improvement in the transverse and radial components, in addition to a significant improvement in the normal component. Including data from subsequent Titan flybys continued to improve the ephemeris, but to a much lesser extent.

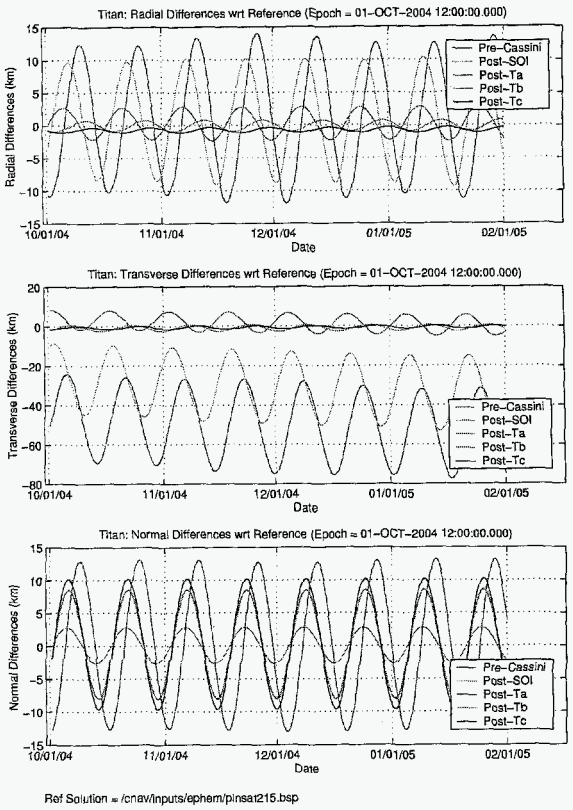

Figure 11 Titan Ephemeris Evolution

As would be expected, in addition to the improvement in Titan's ephemeris, the uncertainties were also significantly reduced as a result of the Ta and Tb flybys, as shown in table Table 12.

Table 12: Titan Ephemeris Uncertainty Reduction During the Titan-a and Titan-b Flybys

Titan Ephemeris Component		Pre-Flyby Uncertainty*	Post-Flyby Uncertainty*
Titan-a			
	Radial	4.06	2.19
	Transverse	22.40	0.74
	Normal	5.85	1.00
Titan-b			
	Radial	1.13	0.36
	Transverse	1.20	0.20
	Normal	0.46	0.31

*Formal 1-σ uncertainties in km

A similar improvement can be seen in Saturn's ephemeris. Figure Figure 12 is a plot of the evolution of Saturn's ephemeris, and shows the same data evolution as figure Figure 11, except the Pre-Cassini case is omitted because it washes out the remaining cases. The differences between sat215 and the Pre-Cassini case are approximately 35 km, 270 km, and 65 km in the radial, transverse, and normal components, respectively. This demonstrates the considerable improvement in Saturn's ephemeris that was obtained using optical navigation images taken before SOI. Figure Figure 12 shows the further improvements that were made with the Ta and Tb flybys. While the radial and transverse components have not changed significantly since that time, the normal component *continues* to evolve.

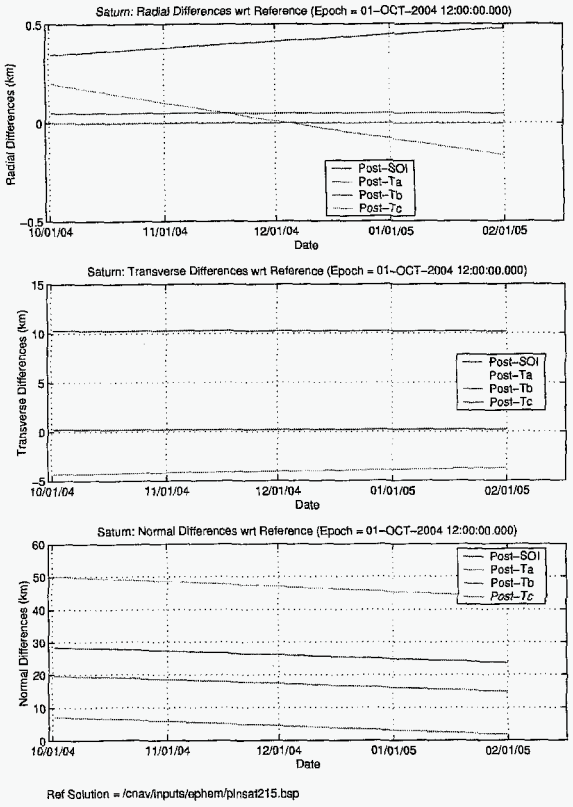

Figure 12: Saturn Ephemeris Evolution

Similar improvements demonstrated in figures 5 and 6 were obtained for most of the remaining satellites throughout the first two Saturn orbits. These improvement were made possible by Saturn's ephemeris improvement in addition to dynamic interaction between the satellites that was observed in the data.

In addition to the improvement in the Saturn system ephemerides, the GMs of Saturn and it's major satellites were also significantly improved as a result of the first two orbits. Table Table 13 shows the progression of the GM values and uncertainties of the Saturn, Titan, Hyperion, and Iapetus. The addition of optical navigation images and data near SOI resulted in a *reduction of all of the uncertainties* except for Iapetus, which was scaled up due to the large variations in the estimate at the time. The Ta and Tb flybys resulted in a significant reduction in the GM of Titan, Hyperion and Iapetus. Titan's GM uncertainty was reduced because

of the close flyby and Hyperion's was reduced because of it's resonance with Titan, as discussed previously.

A reduction of Iapetus' GM uncertainty resulted from a close approach before the Ta flyby of 1.1 Mkm. Subsequently, the Ta and Tb flybys reduced the uncertainty even further because of the resulting determination of the Saturn system barycenter. Being the third largest satellite and it's large distance from Saturn, it's orbit has a significant effecton the Saturnian system barycenter, thus improvements in the barycenter knowledge improve Iapetus' GM estimate. The GM uncertainty of Iapetus was very important to the navigation of the probe mission because of a close approach to Iapetus that occurred after probe separation. Without the uncertainty reduction that occurred during the first two orbits, this event would have resulted in a failure to comply with the probe targeting uncertainty requirements. The shift in Saturn's GM uncertainty after the Tc flyby was mostly due to the inclusion of VLBA data in the Saturn ephemeris model development. The value was later increased again (and the uncertainty dramatically reduced) during four orbits of Saturn during which Cassini did not have a close encounter with any of the satellites.

Table 13: GM Improvement and Uncertainty Reduction

DCO	Saturn*	Titan*	Hyperion	Iapetus
sat143	672±42.18	8.08±1.01	0.720±1.400	129.65±1.34
SOI	635±16.36	7.93±0.265	0.720±0.350	122.17±2.23
Ta	601±16.47	8.03±0.100	0.527±0.100	121.02±0.769
Tb	576±14.93	8.25±0.033	0.379±0.006	120.73±0.174
Tc	516±13.57	8.17±0.040	0.373±0.006	120.54±0.016
sat215	585±00.40	8.19±0.018	0.375±0.003	120.50±0.010

*Saturn GM = Value+37940000, Titan GM = Value+8970

TITAN POINTING RESULTS

One key performance index that is tracked is the pointing uncertainties and errors that are present during a close approach to a body. Figure 13 shows formal one-sigma pointing uncertainties of the final official delivery to the science team before the Ta flyby (the OTM-4 maneuver design delivery). Because of the mis-modeling discussed previously, the actual pointing error was larger than the formal uncertainties. The pointing requirements, shown by the dotted lines, were not met for the Titan-a flyby, which was an expected result (ref. NavPlan). The requirements are 0.79 mrad for altitudes greater than 30,000 km and 1.02 mrad for altitudes between 20,000 and 30,000 km. There is no requirement for altitudes less than 20,000 km.

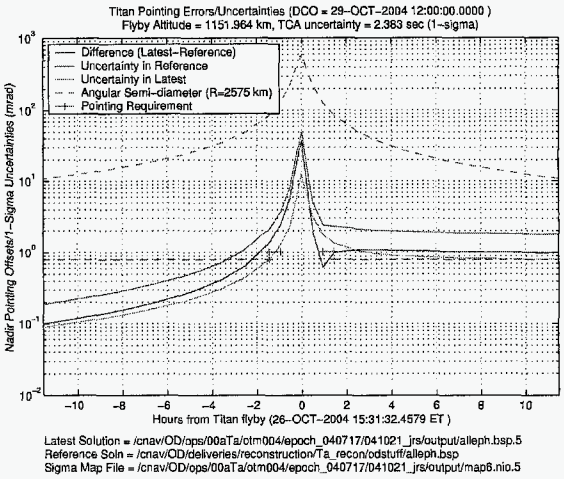

Figure 13: Pointing Uncertainties and Errors Associated with the Final Pre-Titan-a Navigation Delivery

Figure 14 shows formal one-sigma pointing uncertainties of the final official delivery to the science team before the Tb flyby (the OTM-7 maneuver cancellation and Dione pointing update delivery). The actual pointing error was larger than the formal uncertainties until near the time of closest approach, at which time the errors became quite small. The pointing requirement were met for the Titan-b flyby, which was also an expected result (ref. NavPlan). It is important to note that even though the flyby errors were larger than one-sigma, the pointing requirements were still met, which is the most important performance metric for the collection of science data.

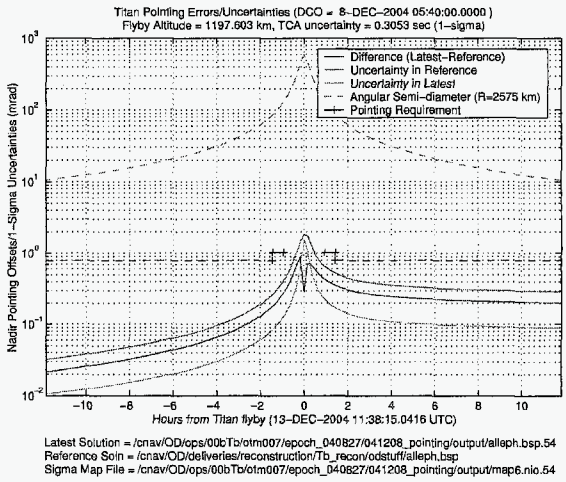

Figure 14: Pointing Uncertainties and Errors Associated with the Final Pre-Titan-b Navigation Delivery

SATURN SYSTEM AND CASSINI POST-FIT UNCERTAINTES

The reconstructed position uncertainties of 8 satellites and the Saturn barycenter, associated with the 00bTb reconstruction, are shown in Figure 15. The uncertainties are shown in three components: radial, transverse, and normal (r, h x r, and h). The Saturn barycenter uncertainties are relative to the Sun and the other uncertainties are relative to the Saturn barycenter. The periodic nature of the curves is due to the uncertainties varying with the orbit period of each satellite.

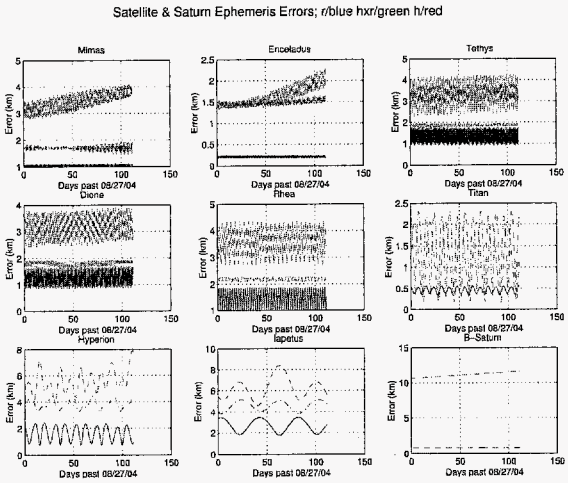

Figure 15. Satellite and Saturn ephemeris errors (radial-blue, transverse-green, normal-red).

The reconstructed position uncertainties for Cassini relative to the Saturn barycenter are shown in Figure 16. These values compare well to the prediction from the Cassini Navigation Plan (ref. 2). The radial values shown below are approximately half the values shown in the Navigation Plan, while the other components are roughly equal.

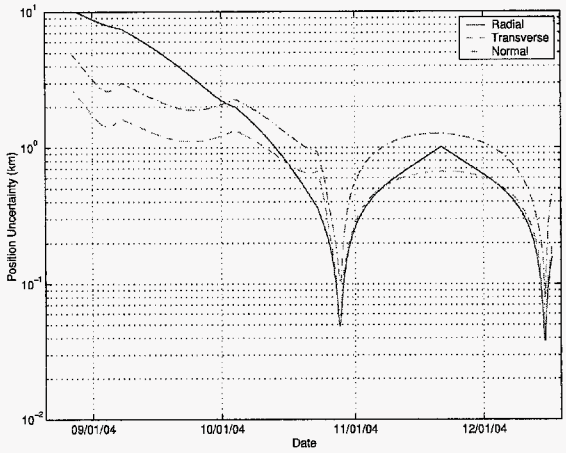

Figure 16. Cassini position uncertainties relative to the Saturn barycenter.

Figure 17 and Figure 18 are overlap plots between the 00bTb reconstruction trajectory and the 00aTa [Roundhill, 2005] and 00cTc [Bordi, 2005] reconstruction trajectories, respectively. In comparison to the position uncertainties shown in Figure 16, the reconstruction trajectories are in good agreement. The main differences between the Ta and Tb reconstructions are the estimation of Hyperion's GM, the Ta flyby thruster modeling, and the inclusion of the Tb flyby in the data arc. The main difference between the Tb and Tc reconstructions is the Saturnian system improvements associated with the Tc flyby.

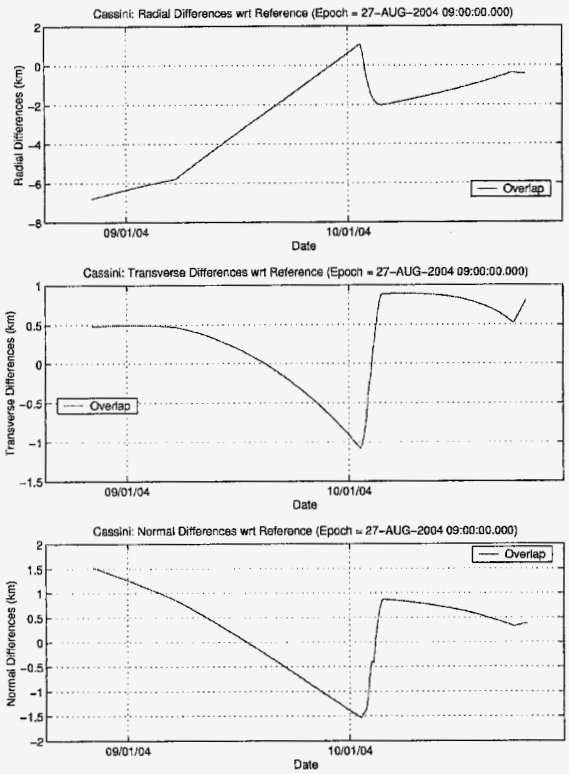

Figure 17: Overlap Between the Tb Reconstruction and the Ta Reconstruction

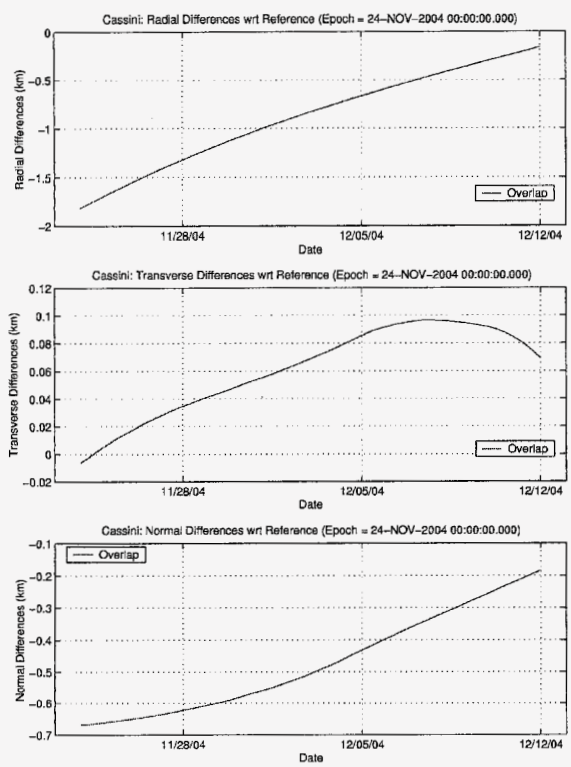

Figure 18: Overlap Between the Tb Reconstruction and the Tc Reconstruction

CONCLUSIONS

All reconstruction navigation requirements were met during this phase of the mission. These requirements include reconstruction pointing accuracies of better than 0.45 mrad for Saturn and the icy satellites and time of closest approach accuracies of better than 300 milliseconds for Saturn, Titan, and all of the targeted icy satellites (which only included Titan for this reconstruction period).

Maneuver execution errors for OTMs 3-6 were all sub-sigma except for the 1.3-sigma error in the OTM-4 ΔV. The reconstructed trajectory did not pass within the Ta one-sigma control dispersion. There was a control error of approximately two-sigma in the B-plane and altitude and five-sigma in TCA. The reconstruction also shows a two-sigma error in the B-plane and altitude and four-sigma timing error associated with the final pre-Ta OD delivery. The reconstruction passed within the Tb one-sigma control dispersion in the B-plane, altitude, and timing, however the final pre-Tb OD delivery, which was used for the Dione pointing live-update, contained a two-sigma error in the B-plane and altitude and a one-sigma timing error. Titan ephemeris errors were the dominant factor in the Ta and Tb flyby prediction errors.

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REFERENCES

Antreasian, P. G, et al., Cassini Orbit Determination Performance During the First Eigth Orbits of the Saturn Satellite Tour, AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, California, U.S.A., 7-11 Aug., 2005.

Roth D. C., et al., Cassini Orbit Determination From Launch to the First Venus Flyby, *AIAA/AAS Astrodynamics Specialist Conference*, Boston, Massachusetts, U.S.A., 10-12 Aug., 1998.

Guman M. D., et al., Cassini Orbit Determination From First Venus Flyby to Earth Flyby, *AAS/AIAA Space Flight Mechanics Meeting*, Clearwater, Florida, U.S.A., 23-26 Jan., 2000.

Roth D. C., et al., Cassini Orbit Reconstruction From Earth to Jupiter, *AAS/AIAA Space Flight Mechanics Meeting*, San Antonio, Texas, U.S.A., 27-30 Jan., 2002.

Roth D., et al., Cassini Orbit Reconstruction From Jupiter to Saturn, *AAS/AIAA Astrodynamics Specialist Conference*, Lake Tahoe, California, U.S.A., 7-11 Aug., 2005.

Roundhill I. M., et al., Orbit Determination Results for the Cassini Titan-A Flyby, AAS 05-113, *AAS/AIAA Space Flight Mechanics Winter Meeting*, Copper Mountain, Colorado, U.S.A., 23-27 Jan., 2005.

Bordi J., et al., Orbit Determination Results and Trajectory Reconstruction for the Cassini/Huygens Mission, *3rd International Planetary Probe Workshop*, Anavyssos, Attica, Greece, 27 June - 1 July, 2005.

Wagner S. V., et al., Cassini-Huygens Manevuer Experience: First Year of Saturn Tour, *AAS/AIAA Astrodynamics Specialists Conference*, Lake Tahoe, CA, U.S.A., 7-11 Aug., 2005.

Cassini Navigation Plan, JPL D-11621, 1 Aug. , 2003.