AAS 05-312

CASSINI ORBIT DETERMINATION PERFORMANCE DURING THE FIRST EIGHT ORBITS OF THE SATURN SATELLITE TOUR

P.G. Antreasian, J.J. Bordi, K.E. Criddle, R. Ionasescu, R.A. Jacobson, J.B. Jones, R.A. MacKenzie, M.C. Meek, F.J. Pelletier, D.C. Roth, I.M. Roundhill, and J. Stauch*

From June 2004 through July 2005, the Cassini/Huygens spacecraft has executed nine successful close-targeted encounters by three of the major satellites (Phoebe, Titan, and Enceladus) of the Saturnian system. During the third orbit the Huygens probe was precisely targeted for a successful descent to Titan's surface. Current results show that orbit determination has met design requirements for targeting encounters, Huygens descent, and predicting science instrument pointing for targeted satellite encounters. This paper compares actual target dispersions against the predicted tour covariance analyses. To assess orbit determination performance, post-flyby results are compared to OD predictions. Prediction accuracy of the satellite ephemeris is a key challenge for successful navigation. The improvement of this ephemeris through the orbit determination process is discussed.

INTRODUCTION

The Cassini/Huygens spacecraft entered into orbit around Saturn on July 1, 2004. From June 2004 through July 2005, the orbiter has performed nine successful close-targeted encounters by three of the major satellites of the Saturnian system. Six of these flybys specifically targeted Saturn's largest moon Titan, two were with the icy moon Enceladus, Saturn's second closest, and one targeted Saturn's distant moon, Phoebe, during the final approach to Saturn orbit insertion (SOI). During the third orbit and third Titan encounter the European Space Agency's (ESA) Huygens probe was precisely targeted for a successful descent to Titan's surface. While the first year of the Mission's designed four-year Saturn satellite tour has been completed, there are over 40 remaining encounters to navigate before the end of the prime mission. Consistent, accurate, and efficient orbit determination (OD) processes are important elements to successful satellite tour navigation. Current results show that orbit determination has met design requirements for targeting encounters, the Huygens descent, and predicting science instrument pointing for targeted satellite encounters. The nine satellite encounters covered in this report are listed in Table 1 with corresponding orbit characteristics. The achieved times of closest approach (TCA) and achieved altitudes are shown. The satellite encounters occur on either the inbound approach to Saturn periapsis or outbound from periapsis. The Titan-4 (T4) and Titan-5 (T5) encounters are the only flybys thus far to occur after Saturn periapsis.

THE CASSINI/HUYGENS MISSION

Cassini was launched in 1997 aboard a Titan IV launch vehicle. After gravity assists by Venus in April 1998 and June 1999, Earth in August 1999 and Jupiter in Dec 2000, the Cassini spacecraft has

*Members of the Engineering Staff in the Guidance, Navigation and Control Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Table 1 The first nine encounters of the Cassini's Saturn satellite tour.

Encounter		Achieved TCA† (UTC)	TCA Error (sec)	Achieved Altitude (km)	Altitude Error (km)	In or Out§	V_∞ (km/s)	Orbit Period‡ (days)	Inc‡ (deg)	Rev No.
Phoebe	Ph	11-Jun-2004 19:33:37.2	+0.2	2070.9	+70.9	I	6.35	N.A.	17.2	0
Titan-A	Ta	26-Oct-2004 15:30:04.6	−4.2	1174.1	−25.9	I	5.65	47.2	13.8	1(a)
Titan-B	Tb	13-Dec-2004 11:38:15.4	+2.4	1192.3	−7.7	I	5.64	32.0	8.5	2(b)
Titan-C	Tc	14-Jan-2005 11:11:58.8	+3.0	60003.3	+3.3	I	5.37	33.3	5.2	3(c)
Titan-3	T3	15-Feb-2005 06:57:53.1	+0.3	1579.0	+2.3	I	5.58	20.7	0.4	4
Enceladus-1	E1	09-Mar-2005 09:08:02.4	+1.5	501.8	+1.8	I	6.60	20.2	0.21	5
Titan-4	T4	31-Mar-2005 20:05:16.0	+0.2	2403.5	+3.5	O	5.61	16.1	7.5	6
Titan-5	T5	16-Apr-2005 19:11:45.9	+0.1	1027.4	+2.4	O	5.63	18.1	21.6	7
Enceladus-2	E2	14-Jul-2005 19:55:21.4	-0.4	172.6	−2.4	I	8.18	18.3	21.8	12

†S/C event time

‡Conditions after encounter, inclination is wrt Saturn Mean Equator

§Encounter occurs before (In) or after (Out) Saturn periapsis

reached its final destination, Saturn, following the completion of the SOI burn on July 1, 2004. The science objectives of Cassini's four year tour of the Saturnian system are to determine the composition, structure and dynamical processes of Saturn's atmosphere, magnetosphere, rings, and satellites. These are important since the dynamical processes shaping the Saturnian system are believed to be similar to those which created our solar system. In addition, it is believed that Titan's atmosphere is much like that of the primordial Earth and so observations of Titan's atmosphere and morphology could provide insight to Earth's evolution. In conjunction with the Cassini orbiter observations, the Huygens probe objectives are to determine Titan's atmospheric structure and constituents as well as Titan's surface topography.

Since the successful Phoebe flyby (June 11, 2004) and SOI (July 1, 2004), science instruments onboard Cassini/Huygens have returned a wealth of data. In addition to Cassini's remote sensing during close flyby's, the Titan atmospheric descent and landing of Huygens probe have sampled unprecedented in situ data of Titan's atmosphere and soil and has also sent back phenomenal images from Titan's surface. Scientists have already made several new interesting discoveries: Phoebe being a captured moon, volcanism on Titan, evidence for liquid methane, land masses and drainage systems on Titan, several new minor moons, and moon-ring interactions.

CASSINI OD BACKGROUND

After a targeted flyby, the first two tracking passes of radio-metric data help to precisely determine the flyby conditions and the targeted satellite's ephemeris state at that orbital longitude. These post-encounter data also help improve the satellite's orbit significantly. The flyby conditions are then compared to the pre-encounter control or OD prediction to compute an overall 3-dimensional position error measurement. These measurements are shown later for the nine encounters, and this provides a basis to assess the overall performance of the orbit determination or navigation processes. Satellite ephemeris errors were the major navigation error source prior to Saturn orbit insertion. Improvements in the estimates of the satellite ephemeris, Saturn and satellite masses, Saturn zonal harmonics, and Saturn pole vector through the orbit determination process are important for navigating the tour. This paper exhibits the improvements made to the satellite ephemeris and the resultant satellite position uncertainties are compared to predictions given in the Cassini Satellite

Tour Navigation Plan (Nav Plan).[1] This paper also compares the predicted tour covariance analysis as specified in the Nav Plan to the rev-by-rev high-fidelity covariance analyses, which are generally performed one and one half orbit revolutions before each encounter using the latest tracking schedules, updated dynamic models, and latest OD filter assumptions. Actual errors are then continuously compared to these covariance analyses for tracking the OD convergence of orbit errors leading up to encounters.

The OD results of Cassini's interplanetary journey are reported in papers Roth, et al[2], Guman, et al[3], Roth, et al[4]. Roth, et al[5] describe the orbit determination results during the final approach to Saturn which encompasses the Phoebe flyby. Roundhill, et al [6] report the OD results for the first orbit in the Saturnian system after SOI leading up to the first Titan encounter (Titan-A or Ta) on October 27, 2004. Stauch, et al[7] summarize the next encounter, Titan-B (Tb) OD results and strategies leading up to the Huygens probe mission in December 2004. Bordi, et al[8] explain in detail the OD strategy, and results which led to the successful landing of the Huygens probe on Titan during January 14, 2005. The Titan-C orbit, which involved the probe mission, was unique and the details involving the probe will not be discussed in this paper.

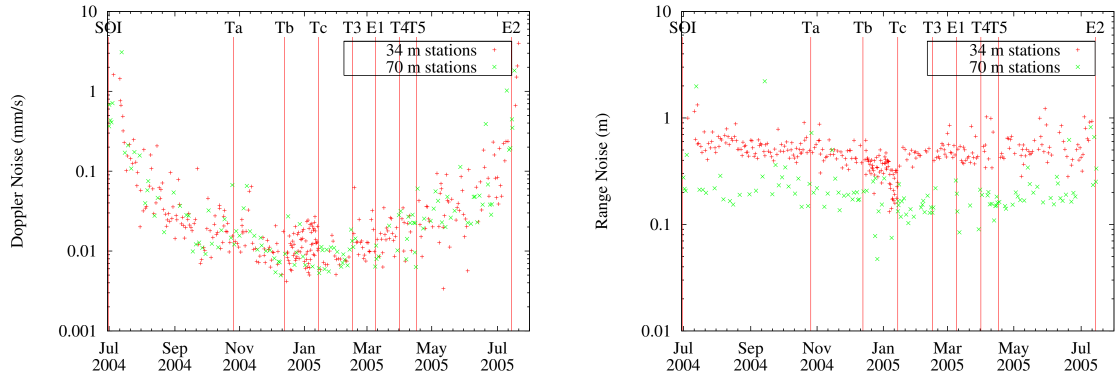
ORBIT DETERMINATION OBJECTIVES

During the prime mission, the Navigation Team's (Nav) main objective is to keep Cassini on the designed satellite tour trajectory.[1] Three Orbit Trim Maneuvers (OTMs) are generally planned per targeted encounter: the apoapsis maneuver targets the trajectory to maintain the designed upcoming encounter flyby conditions, the approach maneuver at -3 to -6 days before the encounter to correct the trajectory from maneuver and OD dispersions, and the encounter +3 day (or more) clean-up maneuver to compensate for flyby errors. Details of the maneuver design strategy are described in the Nav Plan and the performance of the maneuvers (including the OD reconstruction estimates) to date is given by Wagner, et al[9]. OTMs are performed on either the S/C's 445 N bi-propellant Main Engine (ME) or on the four 0.9 N (co-aligned with the ME) monopropellant Reaction Control System thrusters.[9]

Three main objectives of the Orbit Determination (OD) Team are: 1) to perform covariance studies for trajectory designs or redesigns in order to determine navigational capabilities of meeting requirements, 2) to routinely estimate and improve the predictions of the spacecraft (S/C) trajectory as well as the ephemerides of Saturn and the major Saturnian satellites (in order of distance from Saturn, these include the nine moons, Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus and Phoebe), 3) to reconstruct the S/C, Saturn and the satellite ephemerides after the fact.

The predicted S/C, Saturn and satellite ephemerides are provided to the project, Deep Space Network, Science and Nav Teams for designing OTMs, computing tracking antenna frequency predicts, or planning sequence updates. Occasionally, these predictions are used to update the tour reference trajectory such as the recent tour modification to accommodate a unique close flyby of Tethys prior to the planned Hyperion flyby in September of 2005.[10] In order to verify the feasibility of these reference updates a covariance study like that described in ref[11] is performed.

Generally, five days prior to encountering the target satellite a final approach maneuver is designed to correct the S/C trajectory and realign it to the designed flyby conditions. For each flyby, a S/C onboard sequence of science observing activities including instrument pointing is based on the latest navigation reference trajectory at the time of its inception. These are programmed several months before the targeted encounter and remain somewhat inflexible to inevitable changes in the estimates of the S/C trajectory and satellite ephemeris. To overcome this, there are strategic opportunities for updating the instrument pointing vectors prior (5 days or more) to an encounter or occultation (ring or atmosphere). OD solutions with the latest data up to the 5 day requirement



(a) 2-Way Doppler

(b) Range

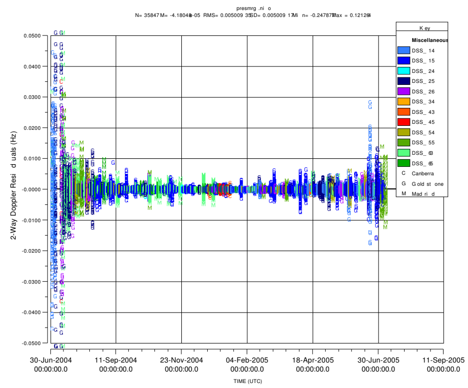
Figure 1 Radio-metric data noise: Doppler in (a) and range in (b)

are delivered to support these 'live' updates. The latest S/C to satellite (or Saturn) pointing vectors are compared to those from the reference trajectory and the latest dispersions are computed. These dispersions are tracked (comparing current ops solutions to covariance studies) in order to identify times when a pointing update is meaningful, that is, when the dispersion is generally less than the correction. Precise instrument pointing to targeted and non-targeted satellites levy requirements for OD predicted $1-\sigma$ accuracies at better than 1.02 mrad for flyby altitudes between 20,000 – 30,000 km and 0.79 mrad for altitudes greater than 30,000 km.

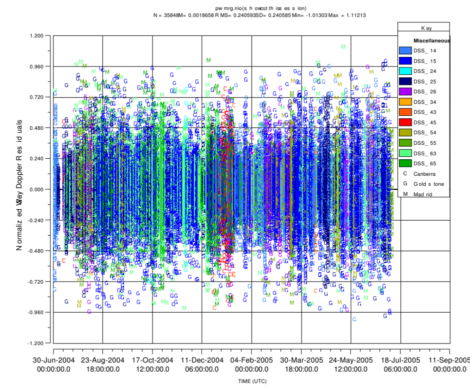
Tracking Data

Cassini's orbit determination is dependent on 2-way X-Band Doppler and range tracking data acquired via NASA's Deep Space Network (DSN) and onboard optical navigation images (opnavs) of the major Saturn satellites against a background of known stars. Generally, one nine hour DSN tracking pass of radio-metric data is acquired per day while 3 to 6 opnav images are shuttered per day. The ranging signal is configured with adequate signal strength at Saturn's distance to acquire data on 5 minute cycle times for range noise of 1 m or better. Because the science instruments are fixed-mounted to the S/C bus, radio-metric data are generally not acquired up to twelve hours before and after targeted encounters since the observing geometries preclude pointing the S/C's High Gain Antenna to Earth for telecommunications. Due to the high declination of Saturn, Cassini is tracked exclusively by the northern DSN stations in Madrid, Spain and Goldstone, CA with the exception of an occasional Canberra, Australia pass.

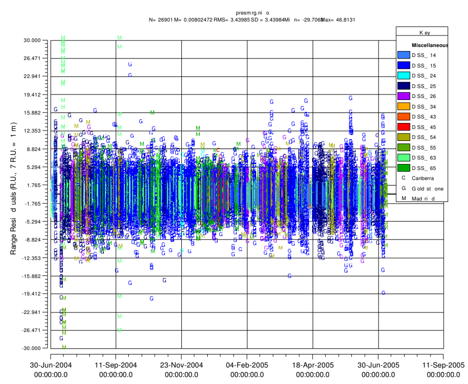
The Doppler and range tracking data are weighted on a per-pass basis to the standard deviation of their residuals multiplied by a scale factor of 3.36. This scaling deweights the data to account for long-term solar plasma noise characteristics. Pass-to-pass data noise is generally better than 0.1 mm/s (for 60 sec count time) for 2-way Doppler data and 1 meter for the range data as shown in Figure 1. As such, the data weights account for these statistics from pass to pass. The better signal-to-noise capabilities of DSN's 70 meter antennas than the smaller 34 meter dishes is evident in the better range noise as exhibited in Figure 1b. Once a year (July in 2004 and 2005), solar conjuction of Saturn as viewed from Earth occurs and the radio signal passing close to the sun is strongly affected by the solar plasma's charged particles. During this time, the Doppler data is deweighted and the range data is subject to deletion especially for Sun-Earth-S/C angles of 5 deg or less. For most of the current tour, the Doppler data has been compressed with 5 minute count times. Data acquired before and after maneuver executions are compressed to a more frequent count time of 60 sec. Because of the HGA mount, no tracking data are acquired during OTMs and occasional



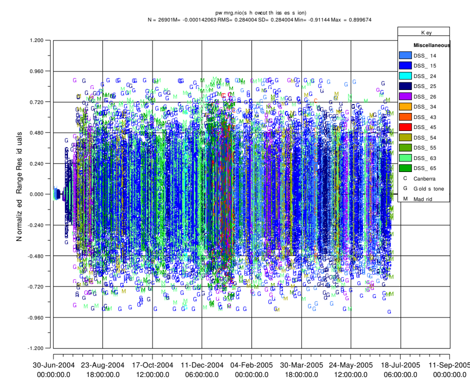
(a) Actual



(b) Normalized



(c) Actual



(d) Normalized

Figure 2 2-way Doppler (a) & range (c) residuals from July 1, 2004 through July 22, 2005. Residuals normalized by their weights are shown in (b) and (d) respectively.

small force ΔV events (as explained below).

The measured variability of the Earth's ionosphere and troposphere is used to calibrate the radio data. Corrections to Earth's polar motion and timing are also applied to the measurement models. Errors due to station locations (2-3 cm), troposphere (1 cm wet, 1 cm dry), ionosphere (5 cm day and 1 cm night), and Earth orientation (2 cm) are all considered in the OD filter. Per-station and per-pass ranging biases are estimated with *a priori* uncertainties of 1 meter and 3 meters, respectively.

The Doppler and range residuals are shown in Figures 2a, and 2c from July 1, 2004 through mid-July 2005. These residuals normalized by their weights are also displayed in Figures 2b, and 2d. The Doppler residual plots show how the noise characteristics increase during the solar conjunction periods (July 2004, 2005). The ranging biases estimated per pass are displayed in Figure 3. A few outliers during the solar conjunction of July 2004 have been removed in order to view the outstanding performance of the DSN's ranging systems. These biases are well under 3 meters while the overall constant station biases are usually much less than 1 meter.

Three to six opnav images of any of the nine satellites are acquired daily by Cassini's narrow angle

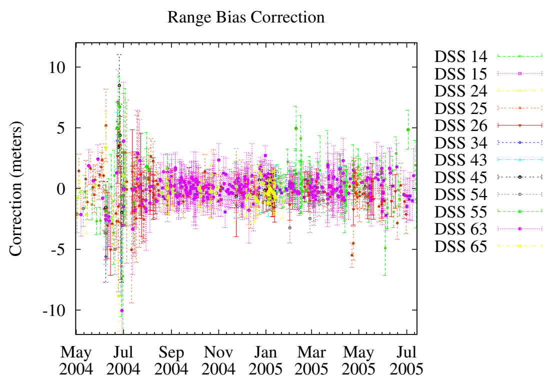


Figure 3 Range biases per tracking pass.

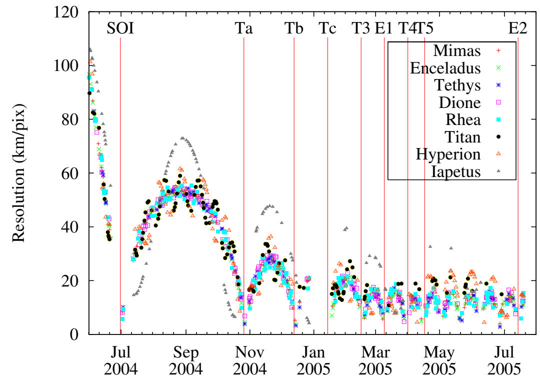


Figure 4 Resolution of opnav images.

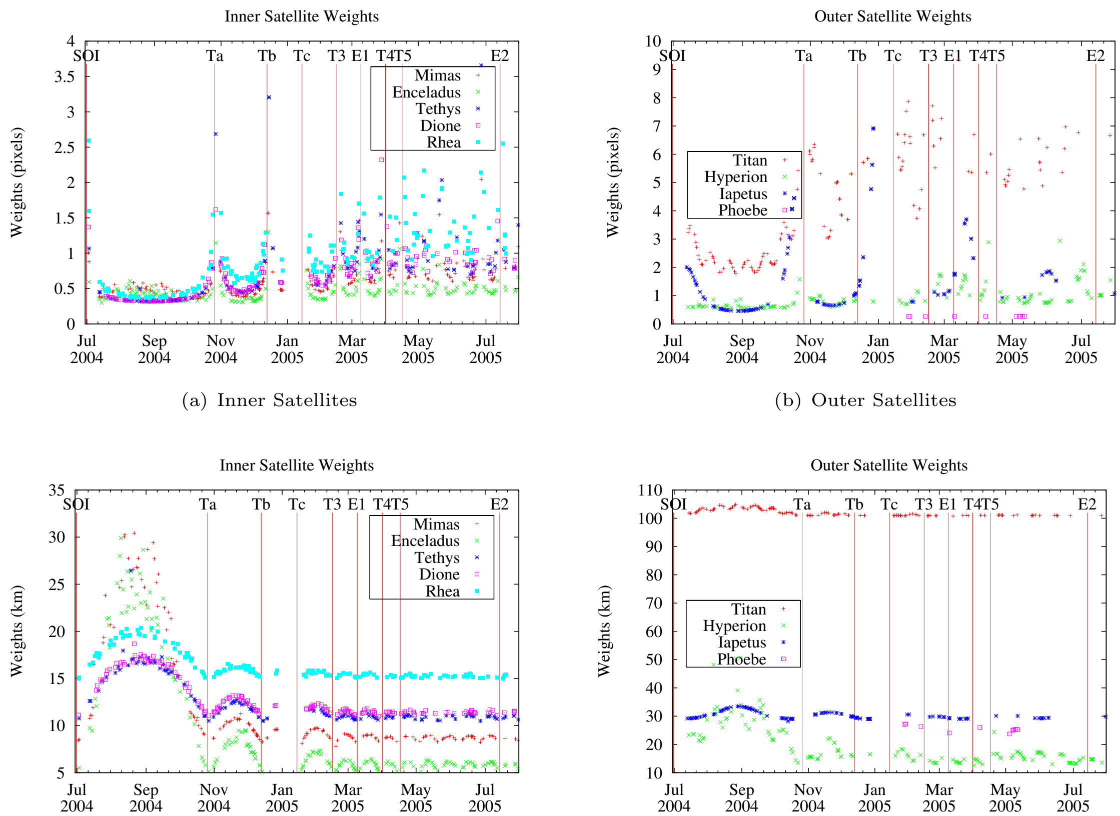
camera which has a 6 mrad field of view and a 2000 m focal length. The camera's Charged-Couple Device contains 1025 x 1025 pixels giving the camera a resolution of approximately 6 μrad/pix. The centers of the known stars and the satellites's diameters are measured in the image pixel (x-axis) and line (y-axis) directions. Effectively, the opnavs are a two dimensional angular measurement of the apparent satellite's position based on the locations of the stars in the camera's focal plane. The optical residuals are a combined measure of both the S/C and satellite Saturn-barycentered orbit errors projected in the focal plane. Depending on Cassini-satellite geometry, some opnavs will show more sensitivity to the satellite's down-track errors while other's shuttered at their greatest elongations as viewed from Cassini are more sensitive to radial errors. Satellite and/or S/C trajectory parameter adjustments are influenced in the least-squares filter depending on the image resolution, optical weights and satellite and S/C state accuracies. The center-finding accuracy of the satellite centers is limited by the accuracy of the satellite's shape model, variability in surface topography, and albedo. The fuzzy nature and variability of Titan's atmosphere further degrades the center-finding accuracies for Titan opnav images. The unpredictable nature of Hyperion's spin and its non-spherical shape complicates and degrades the accuracy of its opnavs. The drastic variation of Iapetus' albedo also degrades these center-finding accuracies. Center-finding accuracies are on the order of $0.1 - 0.2\%$ of the apparent image diameter for the icy satellites and between $0.2 - 0.4\%$ for Titan. Corrections to the camera pointing (rotation angles about the pixel, line axes and camera boresight) based on the stars are estimated in the OD filter for each image with *a priori* of 1 degree for each axis using a white noise stochastic model. These corrections are usually much less than 1μrad in the angles about the pixel and line axes and less than 0.5 mrad for the *twist* angle about the boresight. Zeroth and first order phase biases are estimated for the Titan opnavs with an *a priori* sigma of 5%.

To properly account for the variable accuracy of the images taken at different ranges from the satellites, the opnavs are weighted using the following algorithm:

$$W^2 = W_{min}^2 + (C \cdot d_a)^2$$

Where W is the weight applied, W_{min} is the minimum weight used (0.25 pixels for all satellites except Titan and Hyperion), C is an apparent diameter scale factor, and d_a is the apparent diameter of the satellite. The diameter scale factors are 0.02 for Mimas, Titan, and Iapetus, 0.04 for Hyperion, and 0.01 for the remaining satellites.

Each opnav also includes background stars to estimate the pointing and the stars are weighted at the larger of 0.1 pixels or their formal point-source sigma. The opnav weights of the inner (Mimas, Enceladus, Tethys, Dione and Rhea) and outer satellites (Titan, Hyperion, Iapetus and Phobe) for



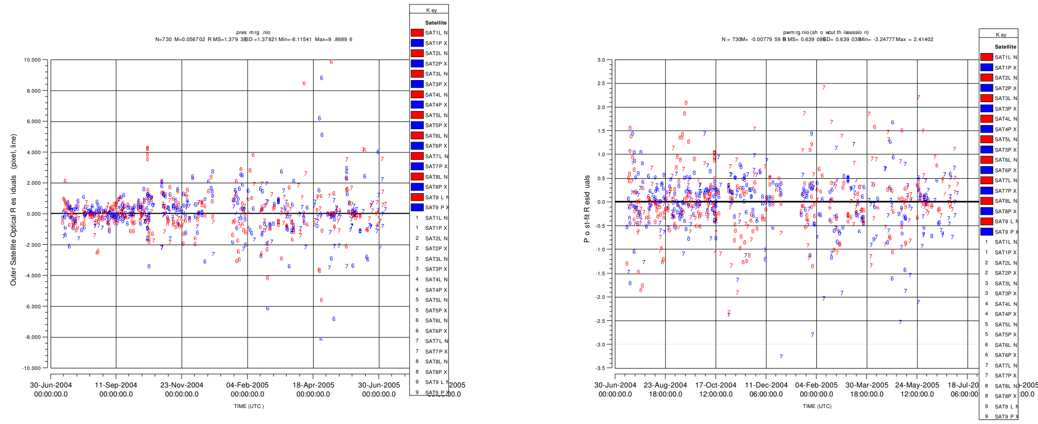
(a) Inner Satellites
(b) Outer Satellites
(c) Inner Satellites
(d) Outer Satellites

Figure 5 Optical weights for the inner satellites (a), outer satellites (b), inner satellites. These are normalized by resolution accuracy for the inner satellites(c) and outer satellites(d).

this first year of the tour are displayed in Figures 5a and 5b, respectively. The resolutions of these images are shown in Figure 4. As shown in this plot, the resolutions of the opnav images after the start of 2005 vary between 5 km/pix during the S/C's Saturn periapsis passage to 30 km/pix at apoapsis distances. Depending on the relative S/C-satellite distance, the weights normalized by their resolution accuracy are given in Figures 5c and 5d. After the Ta encounter, these weights vary from 8 – 11 km for Mimas, 5 – 10 km for Enceladus, 10 – 13 km for Tethys, 11 – 14 km for Dione, 15 – 17 km for Rhea, 13 – 24 km for Hyperion, 29 – 32 km for Iapetus, 23 – 28 km for Phoebe and finally 100 – 102 km for Titan. The optical pixel and line residuals for the inner and the outer satellites are shown in Figures 6a and 7a from July 1, 2004 through mid-July 2005. These residuals normalized by their weights are also displayed Figures 6b and 7b.

Spacecraft Modeling

While in orbit around the Saturn-system barycenter, ignoring the dominant Saturn's point source gravity, the major perturbations affecting the S/C motion in order of significance include thrusting events from OTMs or small forces from the Reaction Control System (RCS), gravity due to the satellites, sun's gravity, oblateness of Saturn, forces due to the S/C thermally-emitted radiation, solar pressure, relativity, satellite oblateness and drag forces during close Titan flybys. The many turns for instrument observations and the counteraction of drag torques during low Titan altitude (1025 - 1200 km) encounters require the S/C attitude to be controlled by the RCS system. The



(a) Actual

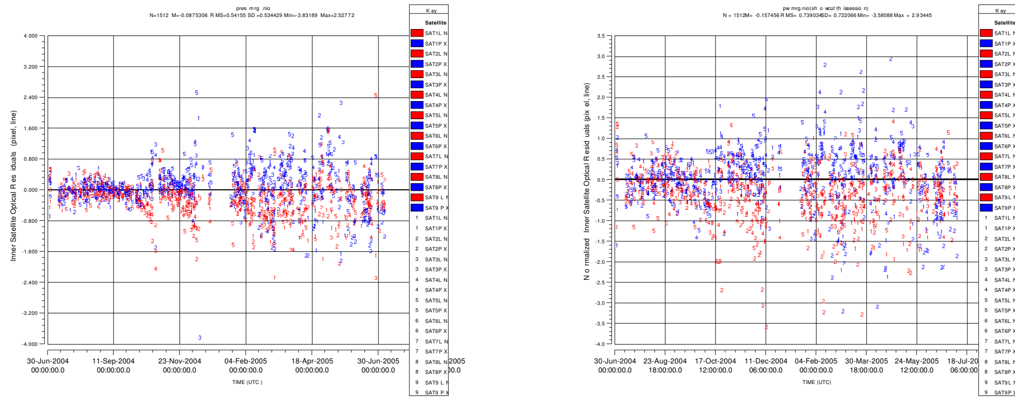
(b) Normalized

Figure 6 Outer Satellite Optical Residuals (July 1, 2004 – July 22, 2005). Residuals normalized by their weights are shown in (b). Symbols: 6 = Titan, 7 = Hyperion, 8 = Iapetus, 9 = Phoebe.

satellite harmonic gravity field effects cannot be determined or separated from these other perturbations without the close-in radio tracking data so these parameters are not included in the OD filter. Although a set of predicted ΔV's is given, the estimation of these events are complicated by the fact that data is not acquired for several hours before to after the flyby. The filter is sometimes unable to discern between the errors in the RCS predicts and the Titan ephemeris and is furthermore hindered by the contribution of drag forces.[7,12] After these encounters the OD Team is under pressure to quickly determine the error from the flyby predictions, the satellite orbit correction and the effects of the RCS thrusting and the drag forces during the flyby. The OD Team only has the equivalent of two passes of post-flyby tracking data to determine these parameters and to predict ahead to the next orbit before an OD delivery is made to the Maneuver Team to design the +3 day clean-up maneuver which sets the S/C on course for the next encounter. The small force ΔV telemetry is used to update the nominal models, if time permits. In the past, this telemetry data resolution was set at 2 mm/s which made it is difficult to calibrate the RCS system. A recent flight software upload in May 2005 had lowered this resolution down to 0.02 mm/s and, based on recent RCS Earth-line ΔV events, this change shows promise in achieving a good calibration of the RCS system.

The finite burn 'rocket equation' is used to model the OTM maneuvers. The maneuver ΔV magnitude, right ascension, and declination of the burn vector are estimated in the filter using an *a priori* uncertainty based on the Gates error model which accounts for fixed and proportional errors.[9] Data cut offs (DCO) for OTM designs are generally set at 2 days or less from their execution. The S/C thermal radiation acceleration is modeled as an exponential decay model with an estimated scale parameter in each of the spacecraft axes. The force due to solar pressure is modeled with a cylindrical bus and parabolical antenna using nominal reflectivity values but no parameters are estimated. At 9.5 A.U. from the sun, magnitude of the thermal radiation acceleration (~ 5.0 nm/s^2) is approximately one order of magnitude larger than the solar pressure acceleration (~ 0.5 nm/s^2). Thrusting due to the RCS events (discussed below) are generally modeled as impulsive maneuvers and only the ΔV magnitude is estimated. Unmodeled small forces (such as solar pressure mismodeling) acting on the spacecraft are accounted for with the use of a set of stochastic accelerations with scale parameters estimated in spacecraft-fixed axes. These are modeled as white noise with spherical *a priori* uncertainty of $0.5 - 1.5$ nm/s^2 and batches every 8 hours. High resolution S/C attitude predicts from the S/C sequences are used in the S/C trajectory integration.

The S/C attitude is three-axis stabilized by the Reaction Wheel Assembly (RWA). Periodic



(a) Actual (b) Normalized

Figure 7 Inner Satellite Optical Residuals (July 1, 2004 – July 22, 2005). Residuals normalized by their weights are shown in (b). Symbols: 1 = Mimas, 2 = Enceladus, 3 = Tethys, 4 = Dione, 5 = Rhea.

RWA wheel momentum dumps or biases are performed one or more times per orbit. These events are performed while the S/C is on Earth point and are thus covered by 2-way tracking data for direct determination of their ΔV contribution. The Attitude and Articulation Control Subsystem Team (AACS) is responsible for sending the OD Team predictions of these RCS ΔV events as they are placed in future sequences. Every six months to one year an RWA friction test is performed to study the health of the wheels. Occasionally, flight software uploads are performed; significant ΔV events occur while the new onboard software is checked-out. Such a significant event occurred less than one month before the Ta flyby as discussed in ref[6]. The OD Team relies on accurate predicts of these events for mapping the S/C orbit to encounters for maneuver designs or satellite pointing predictions so the errors of their predictions are tracked. Doppler data acquired during these events measure the ΔV while the ranging data measures the timing offsets from their predictions.

Generally, 15 – 30 minutes of tracking outage occurs during a ME burn: the S/C spins down the reaction control wheels and transitions the attitude control to the RCS. Under RCS control, the S/C yaws then rolls to burn attitude. After the burn, the S/C rolls then yaws to Earth point, and finally the reaction control wheels are spun up to transition the S/C back to RWA control. During the first yaw turn, the S/C loses contact with the DSN and is subsequently reacquired afterwards. Higher frequency Doppler data is needed to discern between the ΔV events: RWA spin-down, burn (yaw, roll turns included), and RWA spin-up. For smaller burns ($<$ 0.4 m/s), the RCS system is used,[9] the S/C turns to burn attitude on RWA. During these burns, a somewhat looser attitude tolerance is used, this tolerance is tightened after the burn to resume nominal operations, resulting in an additional ΔV in the burn direction. This bias, which could be a significant fraction of the total burn ΔV, is somewhat predictable, therefore the designed burn includes its effects.

Data Arc Strategy

For OD purposes, a new orbital data arc is established at each Saturn apoapsis. This data arc is responsible for OD solutions pertaining to the targeted satellite or Saturn periapsis activities used for clean-up maneuvers 1/2 revolutions later. After initiation, the solutions of this short arc become available as important comparisons to the longer arc which is prime for the upcoming encounter.

OD solutions routinely include estimates of 90 − 150 constant bias parameters, and 10 − 20 stochastic terms. Tracking the satellite parameter estimates and how the dynamics of the Saturnian system is affected is a major challenge of the OD Team. Cassini OD involves fitting the S/C trajectory, Saturn and the satellite ephemeris to the tracking data (both radio and optical) in a least squares sense using the JPL pseudo-epoch state estimation filter. These linear corrections are then used to update the S/C dynamical models and measurement biases as well as the Saturn ephemeris (state, Saturn pole, $J2$, $J4$, and system mass) and the estimated satellite parameters (satellite states, masses). Then the S/C trajectory is numerically integrated following that of all nine satellite orbits. Due to the highly non-linear nature of this complicated system, these orbits are then refit to the data and this process is iterated until the linearized corrections become small enough that the post-fit residuals closely match that of the pre-fit. Parameter estimates are routinely compared to prior solutions, those from other data arcs and various filter strategies. Parameter corrections on the order of formal 1-σ or more usually require further investigation as well as 1 or more sigma corrections in the stochastic parameters from their zero nominals.

To establish a new data arc at a new apoapsis epoch: The current prime long arc is fit up to this epoch, the Saturn ephemeris is corrected, the satellite parameters are corrected and then their orbits are numerically integrated before the S/C trajectory is integrated and the OD is converged, a new S/C initial state is interpolated from this new integrated trajectory. The S/C state uncertainties from the long arc are mapped to this new epoch and this correlated state covariance is generally scaled by 5, the estimated satellite parameters (satellite states, masses, Saturn, pole, $J2, J4$, and system mass) from the long arc fit are used to establish an updated satellite model, the post-fit correlated covariance of these satellite-Saturn parameters are then used as the new arc's *a priori* satellite covariance, the thermal radiation acceleration terms are updated based on S/C mass decrements (from probe release or propellant expended during burns).

Due to the integration and partial derivative errors and increases of the information matrix conditioning during multiple satellite flybys, data arcs rarely extend more than a few days beyond the second encounter. Arcs that cover two flybys and Saturn periapses are difficult to fully converge, i.e. repetitive iterations cannot resolve fully the non-linearities in the system.

Filter Strategy

The baseline filter strategy utilizes the radio-metric and optical data. Baseline filter parameters include the satellite parameters as mentioned above and their unscaled covariance (formal statistics), burn parameters according to the error execution model in ref[9], small force impulsive ΔVs with 5 mm/s *a priori* each, thermal radiation acceleration with uncertainty of 10% on the S/C $z-$axis (aligned with S/C's HGA) and 50% on the x and y axes, stochastic accelerations on the order of 0.5 nm/s^2. The baseline OD filtering strategy is routinely compared to a large set of 50 − 60 filtering strategies that singly bound the filter parameter errors or data noise using loose or tight *a priori* covariances or data weights and data type combination sets. The capability to consistently and efficiently compute these large filtering strategy sets on a daily basis so that their progress can be tracked and compared was provided through the use of the *filter_loop* program that was originally developed for the Mars Exploration Rover mission interplanetary navigation.[13] The overall results of these filter cases show how the individual data types or filter parameters move the solution and give insight into how the baseline case may need to be tuned. Interesting cases include the scaling of the satellite covariance and the removal of inner or outer satellite opnavs.

COVARIANCE ANALYSIS

The predicted tour covariance analysis as specified in the Nav Plan[1] forms the basis of navigation performance and capability. This study, which was completed before tracking schedules and detailed

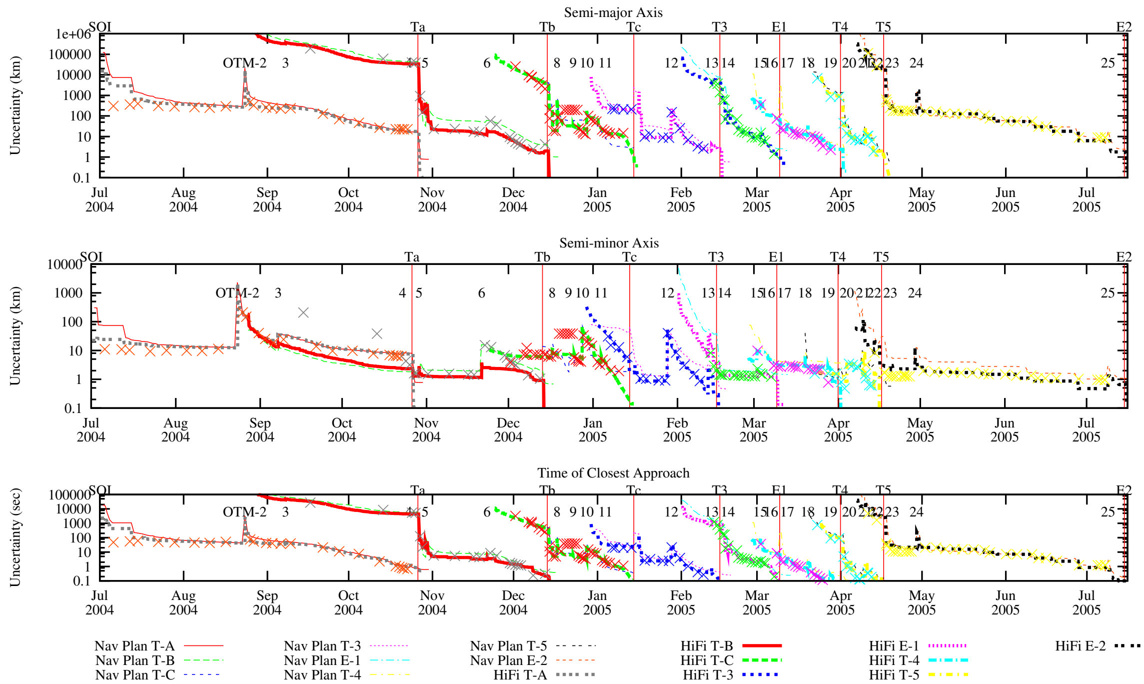


Figure 8 Tracking the OD convergence by comparing the achieved OD statistics (X symbols) during operations compared to the Nav Plan (thin lines) and HiFi covariance studies (thick lines). The locations of the OTMs are indicated by their numbers.

dynamic events were known, made somewhat conservative assumptions on the OD filter models, radio-metric and opnav tracking schedules and data quality. Before a segment or data arc begins, a high-fidelity (HiFi) covariance study is performed using the latest tracking schedules, updated dynamic models, and latest OD filter assumptions. As this new data arc becomes operational, these covariance analyses (as shown in Figure 8) help track the OD convergence of orbit errors and provide a map to track operational OD performance as a function of time leading up to each targeted flyby. The main product of these covariance analyses is the mapping of the S/C dispersions to the encounter B-plane as a function of DCO. The B-plane semi-major and semi-minor axis dispersions are computed as well as the uncertainty in the time of closest approach (TCA). To show how the tracking data is converging or reducing the S/C mapped uncertainties, all thrusting events and filter parameters are included in the filter at each DCO; down-stream events except OTMs are included as *considered* errors since the mapped OTM dispersions to the encounter B-plane are typically much larger than the OD errors and thus would mask the OD convergence. Instead these OTM events are included into the filter at their execution times. Their contributions to the OD errors are shown in Figure 8 by the relatively large spikes in these plots. It is also shown how these dispersions are reduced as the post-burn data is fed into the filter. These rev-by-rev high-fidelity covariance analyses are generally performed one and one half orbit revolutions before each encounter. During the progression or evolution of the data arc for a particular targeted encounter, the current OD statistics are routinely plotted in Figure 8(designated by the X symbols) against the HiFi and Nav Plan covariance studies to ensure that the OD is converging (errors are declining) as expected from these studies. As shown in Figure 8, the HiFi analyses typically show better statistics than the

Nav Plan. This is expected and is directly attributed to the conservatism in the Nav Plan study which assumed that the S/C would be under RCS control for each encounter with ΔV uncertainty of 160 mm/s applied in the filter. The Nav Plan also assumed the stochastic accelerations to be 9 times larger than that of the HiFi value. Departures in actual operation solution statistics shown in Figure 8 can be attributed to the following: the late addition or removal of RCS ΔV events, optical or radio data outages, and changes in satellite covariance scaling.

RESULTS OF TARGETED ENCOUNTERS

Orbital Trim Maneuvers (OTMs) target for satellite encounters using the satellite-centered orthogonal B-plane coordinate frame where the S axis lies parallel to the S/C's approach asymptote, the R and T axes form the impact B-plane, and T lies in the Earth-Mean-Orbit of J2000. The B-vector points within the B-plane from the center of the coordinate system to where the S/C approach asymptote pierces this plane.

Figure 9 shows the B-plane results for each of the nine targeted satellite encounters. These results are presented using the formal 1-sigma statistics. These statistics don't represent the full uncertainty of the OD solutions due to the complexity of the satellite system, but they do provide a means to gauge the OD performance. The final reconstructed solution which incorporates the post-flyby radio-metric data is plotted against the final approach maneuver target and dispersion. These reconstructions usually determine the satellite-relative flyby position to better than a few 100 m. Occasionally, the final approach (-3 day) maneuver was canceled, and in these cases the reconstructed solution is compared against both the final pre-encounter OD solution and the last targeting maneuver (at apoapsis). In some cases, this final pre-flyby OD solution was used for updating the sequence instrument pointing vectors.

Results of the encounter conditions for these nine targeted satellite encounters are listed in Table 2. Target miss parameters are given as a difference in the position from the target in the B-plane and in the time of closest approach. The table indicates whether the post-flyby reconstruction is compared to the last navigation control point, which includes an OTM that targeted the trajectory to the desired aim point and the associated maneuver execution errors in the dispersion, or to the last pre-encounter OD solution, which was used to cancel the final approach maneuver or was used for the last science-instrument pointing update. Generally, for instances where the final approach maneuver had been canceled, the last nav control point would have occurred at the apoapsis maneuver (Apo); these maneuver error contributions would normally dominate the target dispersions so that the miss in terms of the standard deviation is relatively small. Also given in Table 2 are 3-dimensional position errors for each encounter which are expressed in terms of the formal predicted dispersions by the following equation:

$$\sigma_{3-D} = \sqrt{\Delta B^T \Lambda^{-1} \Delta B}$$

where ΔB is the target miss vector (reconstruction – prediction) in the encounter B-plane:

$$\Delta B = \begin{bmatrix} \Delta B \cdot R \\ \Delta B \cdot T \\ \Delta TCA \end{bmatrix}$$

and the final nav or OD control B-plane covariance is

$$\Lambda = \begin{bmatrix} \sigma^2_{B \cdot T} & \sigma_{B \cdot T, B \cdot R} & \sigma_{B \cdot T, TCA} \\ \sigma_{B \cdot R, B \cdot T} & \sigma^2_{B \cdot R} & \sigma_{B \cdot R, TCA} \\ \sigma_{TCA, B \cdot T} & \sigma_{TCA, B \cdot R} & \sigma^2_{TCA} \end{bmatrix}$$

Table 2 Encounter Summary (**Error given in terms of formal (unscaled) statistics**)

Target	Last Control Point	Last Maneuver Design	Maneuver Error	Nav or OD Error?	Position Error (km) (1σ)	3-D B-plane error	Delivery Accuracy Probability	Reason for Miss
Ph	-15 day	TCM-20	$< 1\sigma$	Nav	73.6	0.5	3%	
	-5 day	Phoebe Pointing Update	N.A.	OD	13.8	1.3	36%	
T-A	-3 day	OTM-4	1σ	Nav	40.3	−−	−−	Titan eph error ($\sim$35 km, $\sim 2\sigma$), OTM-4 $\sim 1\sigma$ execution error
T-B	Apo	OTM-6	$< 1\sigma$	Nav	22.5	0.3	0.7%	
	-5 day	OTM-7	Canceled	OD	5.5	3.0	97%	Titan eph error ($\sim$4 km, $\sim 2\sigma$)
T-C	-10 day	OTM-10a	$\sim 1\sigma$	Nav	37.3	1.8	64%	OTM-10a $\sim 1\sigma$ execution error, & Unobserved OTM-10 error
T-3	-3 day	OTM-13	$< 1\sigma$	Nav	4.6	1.5	48%	Unobserved OTM-12 error
E-1	Apo	OTM-15	$< 1\sigma$	Nav	10.4	0.6	5%	
	-5 day	OTM-16	Canceled	OD	3.1	2.4	88%	Enceladus eph error &($\sim$4 km, $\sim 2\sigma$)
T-4	Apo	OTM-18	$< 1\sigma$	Nav	8.3	1.3	36%	
	-5 day	OTM-19	Canceled	OD	9.1	−−	−−	Titan eph error &($\sim$10 km out-of-plane error, $\sim 4\sigma$)
T-5	-3 day	OTM-22	$< 1\sigma$	Nav	0.5	0.3	0.7%	
E-2	-6 day	OTM-25	$< 1\sigma$	Nav	6.2	0.8	11%	

Phoebe

Details of the Phoebe flyby are reported in ref[5]. On May 27, 2004, during the final approach to Saturn, TCM-20 targeted a 2000 km flyby of Phoebe on June 11, 2005. The maneuver execution error, reported in ref [5], was below 1σ. At five days before the encounter, an OD solution was delivered in order to update the instrument pointing vectors in the onboard sequence. The Phoebe B-plane in Figure 9a shows the TCM-20 target and dispersion, the last delivered OD for the 'live' update before the encounter and the achieved (reconstructed) flyby results. As shown in Table 2, the altitude difference from the TCM-20 target was approximately 71 km higher. Figures 19 and 25 show the improvements made to the Phoebe mass and ephemeris estimates. Phoebe's orbital elements were later improved from post-SOI data, opnavs taken in early 2005 and the recent set of orbits between T5 and E2 because of the improved Saturn-system mass determination (discussed below).

Titan-A

The challenges of the Ta OD and the final results are discussed in ref [6]. Due to its extended atmosphere, the center-finding algorithm had difficulties with the Titan opnavs on approach to the Oct 26, 2004 Ta encounter. It was this algorithm that created the optical observables for determining Titan's ephemeris prior to this first Titan encounter. The optical data was unable to determine the relatively large 40 km miss at the Ta flyby. This was about 4.9 σ relative to the formal statistics which we believed did not give the true error due to the difficulty of the center-finding of Titan opnavs. Most of this error was due to Titan's ephemeris estimate which shifted approximately 40 km ($2-\sigma$) in its down-track position and 5 km in the out-of-plane direction. This determination of the Titan ephemeris after the Ta encounter was made difficult because the S/C was on RCS control, and it experienced atmospheric drag with no radio-metric data during the flyby. The targeted 1200 km altitude was missed by 26 km, so that the S/C flew a bit lower (1174 km). The last targeting maneuver for Ta, OTM-4, was found to have over performed by a little more than 1σ yet this was not the reason for the miss. Figure 9b compares the reconstruction against the OTM-4 and OTM-3 dispersions in the Ta B-plane.

Titan-B

The OD leading up to the Dec 13, 2004 Tb encounter was just as challenging as Ta. Although the Titan ephemeris had been improved at Ta, it was found that different assumptions for the RCS ΔV events and the atmospheric drag during the Ta encounter produced different changes in Titan's ephemeris, mostly in its orbital eccentricity. This concern was lessened by the fact the Tb encounter would take place at Titan's same orbital longitude as the Ta event. The nominal execution of the apoapsis burn, OTM-6, placed Cassini on course for the Tb flyby. The solutions produced for the final approach maneuver, OTM-7, showed that there was no reason to perform OTM-7 since the solutions were close to the target ($\sim$ 20 km). Even though OTM-7 was canceled, the OD delivery for its final design was used for an update of the onboard pointing parameters. As shown in the Tb B-plane (Figure 9c), and in Table 2, the control error for OTM-6 was approximately 23 km, well under 1σ, especially since it had a relatively large dispersion. The OD delivery for OTM-7 was found to be only 6 km off from the reconstructed value as seen in Table 2. Since the formal statistics of this OD were very small, the reconstruction was shown to be approximately 3σ off this prediction. The OD filter strategy that removes the inner satellite opnavs from the filter did show better predictions (as compared to the reconstruction) at the time of the OTM-7 DCO. The Titan ephemeris was estimated to be in error by approximately 4 km which was 2 σ relative to its *a priori*. The S/C flew 7.7 km lower than the targeted altitude of 1200 km. From Figure 23, the eccentricity of Titan became better determined from this flyby. More details of this encounter and the modeling of events surrounding the close flybys of Ta and Tb will be discussed in ref[7].

Titan-C

As mentioned, the Jan 14, 2005 Tc results are discussed in ref [8]. The error in the Tc flyby as shown in Figure 9d and Table 2 was 37 km off the target, this represented a nearly 2σ error from the control dispersion of OTM-10a (the Orbit Deflection Clean-up Maneuver, ODMCU). Part of the reason for this error was the last targeting maneuver, OTM-10a, over performed by nearly 1σ. Also, it was found after the Tc flyby that the determination of the OTM-10 (Orbit Deflection Maneuver) in solutions leading up to the OTM-10a design were in error. The post-Tc reconstruction showed the OTM-10 burn to be closer to nominal than the operational solutions indicated, they were over estimating the ΔV magnitude by nearly 10 mm/s (1σ). There was no significant change in Titan's ephemeris.

Titan-3

The T3 OD solutions leading up to the final T3 -3 day targeting maneuver, OTM-13, suffered the same problem as the OTM-10a solutions. Here, the execution errors of the large apoapsis maneuver, OTM-12 (18.7 m/s), were unresolved until after the Feb 15, 2005 T3 flyby (see Figure 9e). The OTM-13 burn performed nominally ($< 1\sigma$). Table 2 shows that the S/C flew 4.6 km (or 1.5σ) from the target. The post-T3 data showed that the pre-T3 determination of the OTM-12 ΔV magnitude estimate was low by only 3 mm/s. However, this was enough error to account for the flyby offset. Again, there was no appreciable change in Titan's ephemeris.

Enceladus-1

Two days after the T3 flyby on Feb 17, 2005, Cassini flew by Enceladus at approximately 1263 km (designated as the E0 flyby). This flyby was non-targeted meaning that no maneuver was designed to achieve a certain flyby target. The radio-metric data before and after this flyby enabled an accurate determination of Enceladus' mass as shown in Figures 12a & b. The uncertainties drop nearly 2 orders of magnitude after the flyby. This mass was verified during the 502 km E1 flyby on March 9, 2005. The OD solutions leading up to the final E1 -3 day targeting maneuver (OTM-16) were very consistent. The final OD for OTM-16 as shown in Figure 9f was only approximately 5 km from the target. It was useless to perform the OTM-16 maneuver as the statistical likelihood of achieving the target was not any better than that of the OD solution since the OD statistics nearly encompassed the target. Therefore, OTM-16 was cancelled. Table 2 shows that with respect to the apoapsis burn (OTM-15), the S/C flew within 10.4 km from its target which was mainly a down-track error (+1.5 sec). Comparing the reconstruction to the OD solution for OTM-16 design in Table 2 reveals that its prediction was only 3.1 km in error. This represents a nearly 2.4σ shift given the formal statistics. The miss was mainly due to a down-track Enceladus ephemeris error of ~ 4 km (which was a 2σ change from its *a priori* ephemeris).

Titan-4

T4 was the first outbound Titan encounter. Even though Titan's ephemeris had already been determined through four flybys, these determinations occurred at the same orbital longitude. It takes at least two flybys at different longitudes to fully determine the six components of the satellite's orbital elements. After the nominal execution of the apoapsis targeting maneuver, OTM-18, the OD solutions leading up to the design of the clean-up maneuver showed very little variation in the solutions as viewed in the T4 B-plane. This was true for various filtering strategies. As a result the final targeting maneuver, OTM-19, was canceled. The apoapsis OTM-18 maneuver dispersion and target are shown in the T4 B-plane in Figure 9g. The final OD delivery for the OTM-19 design is compared against the reconstructed solution. The miss from the OTM-18 target was ~ 8 km while it was 9 km from the final pre-T4 OD. This small error was actually 4.2σ relative to the formal statistics which we didn't believe because the optical data was not providing enough information on Titan's ephemeris. After the encounter, it was found that again the Titan ephemeris was in error, this time there was a large 10 km error in Titan's out-of-plane position which was nearly 4 times its formal statistics. The Figure 23b shows that the T4 flyby significantly corrected Titan's longitude of the ascending node and argument of periapsis.

Titan-5

The orbit from T4 to T5 was the first 16 day orbit of the satellite tour. There will be many more of these to come. Since Titan has a 16 day period, the T5 encounter takes place at the same orbital longitude as the T4 encounter. The T4 encounter data helped to significantly improve the Titan ephemeris knowledge. Figure 9h compares the flyby results for the April 16, 2005 T5 encounter. As indicated in this figure, the actual target for the last targeting maneuver OTM-22 was updated because of an error in the prediction for the RCS ΔV events surrounding the burn. With the nominal execution of OTM-22, the T5 reconstructed results showed remarkable agreement to the final OTM-22 target. As shown in Table 2, this was less than 0.5 km from the corrected T5 target which is only 0.3σ error from the formal statistics. Again, Titan showed no significant changes.

Enceladus-2

The E2 encounter occurred five orbits (89 days) after the T5 flyby. Six days before the encounter, the final targeting maneuver OTM-25 corrected the S/C's trajectory for the low 175 km E2 flyby. As discussed in the next section, these 'empty' revs allowed a better determination of the Saturn-system mass. Furthermore, the inner satellite residuals, especially Enceladus (Figure 7) showed a negative bias, indicating that either the opnavs had a systematic bias or the filter strategy was incorrect. These two facts led us to believe that our current satellite covariance could be over constraining the system so it was decided to scale the covariance up by a factor of three. This scaling the satellite covariance effectively puts more weight on the opnavs. With the nominal execution of OTM-25, the post-flyby reconstruction, as shown in Figure 9i, was only 6 km (0.8σ) from the target. Furthermore, the Enceladus ephemeris changed very little (< 1 km). Reconstruction analysis of the flyby showed that the pre-encounter OD solutions which had more weight on the opnavs moved further from the truth than solutions which placed more weight on the satellite covariance. This flyby showed that the opnavs do appear to have a systematic bias.

SATELLITE EPHEMERIS DEVELOPMENT

The estimation and integration of the satellite ephemeris are a major ingredient in the OD processes and present one of the major challenges to accurate OD. Prior to the final Saturn approach Jacobson [14] supported satellite ephemeris development for the Cassini mission based on the flyby's of the Voyager and Pioneer 11 S/C radio and optical tracking data, US Naval Observatory, Hubble, and Table Mountain astrometric observations as well as numerous historical observations dating back to the 1960's. The large data set used to estimate the satellite ephemeris is important to determine the long period dynamical interactions. To properly compute the satellite orbits, the dynamical environment of the Saturnian system needs to be modeled and estimated. In addition to the Saturn ephemeris, this environment includes the satellites' initial Cartesian state at epoch (January 2, 2004), the Saturn pole position at epoch, the masses (GM) of the satellites, Saturn, the oblateness (J2) and zonal harmonic J4 of Saturn. Through the large data set, meaningful or significant correlations between these parameters are formed in the covariance and provide the mechanisms that allow some parameters to be improved based on the observability of another or how the covariance becomes over constrained. For instance, there exists a $\sim$72 yr period longitude libration of Mimas and Tethys due to their 2:1 mean motion commensurability.[14]

The OD Team frequently interacts during weekly Satellite Working Group and OD meetings to discuss current satellite results, issues, problems and to provide direction for filter strategies and modeling. Jacobson[14] provides the OD Team with periodic ephemeris updates. These include *a priori* satellite-Saturn covariances. It is the belief of the team that this global fit of the satellite ephemeris based on the large data set is superior to the *localized* fit of the OD Team performed during operations on a rev-by-rev basis. It is known that the operational OD satellite ephemeris estimates tend to run-off from those provided from the global fit of the data as the long period terms such as the Mimas-Tethys libration may become lost.

Solutions for the determination of the satellite classical orbital elements are shown in Figure 21 for Mimas & Enceladus, Figure 22 for Dione & Tethys, Figure 23 for Rhea & Titan, Figure 24 for Hyperion & Iapetus and Figure 25 for Phoebe. These formal 1-sigma statistics don't represent the full uncertainty of these orbits nor the mass estimates stated in the next section. It would not be as meaningful to show these estimates with their believed statistics as this would mask the truly complicated nature of this system. These figures show how the data is improving the satellite uncertainties. The change in the Saturn position from JPL's DE-410 ephemeris is approximately 284 km. Table 3 shows that this was a predominately down-track change.

The improvements of these ephemeride uncertainties at each data epoch are compared against the Nav Plan covariance study. These errors are mapped 30, 90 and 180 days from these epochs to show if there are any secular growth in these errors. As shown in Figure 10, the satellite statistics from the operational OD solutions are as good or better than the Nav Plan for most of the year except for

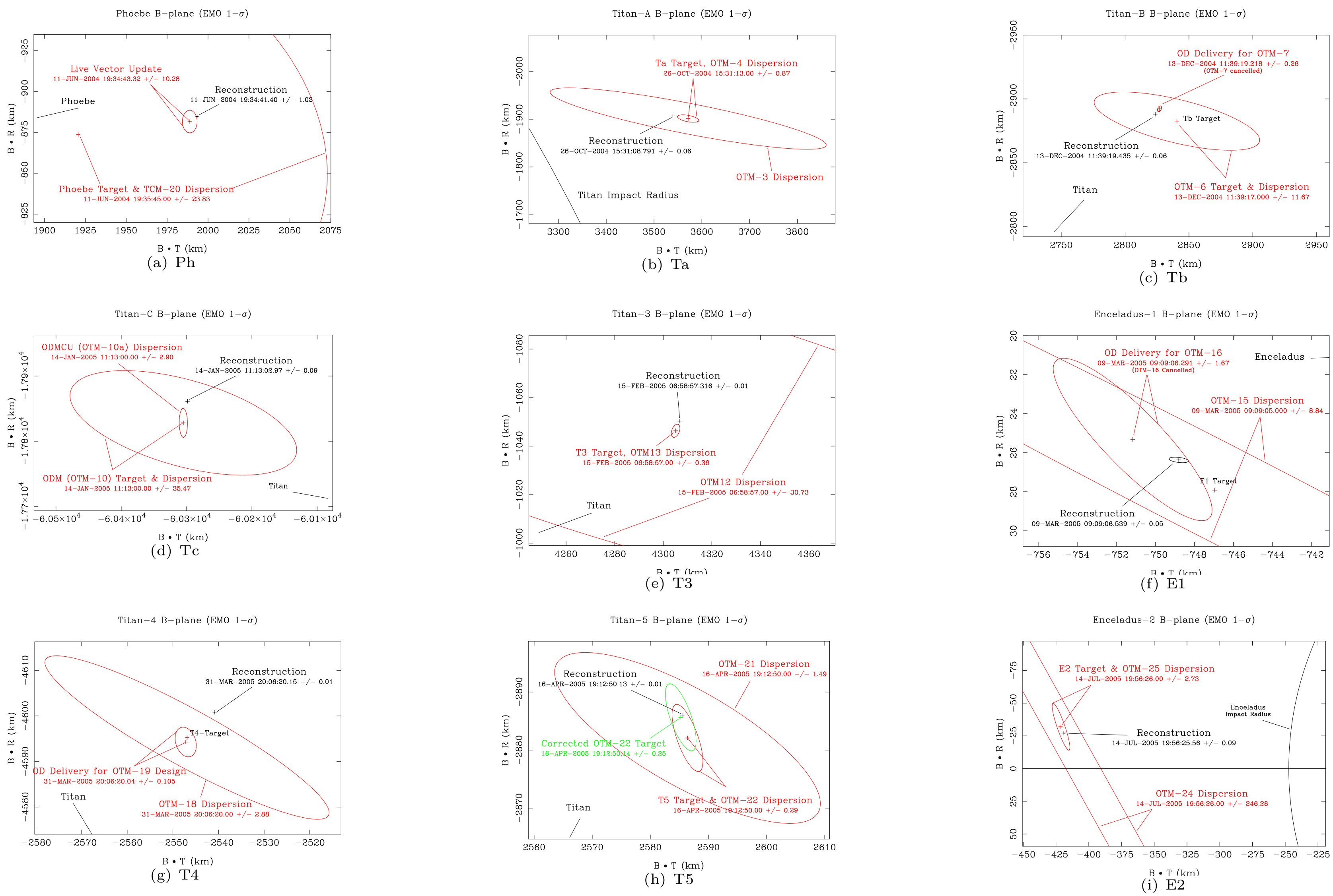
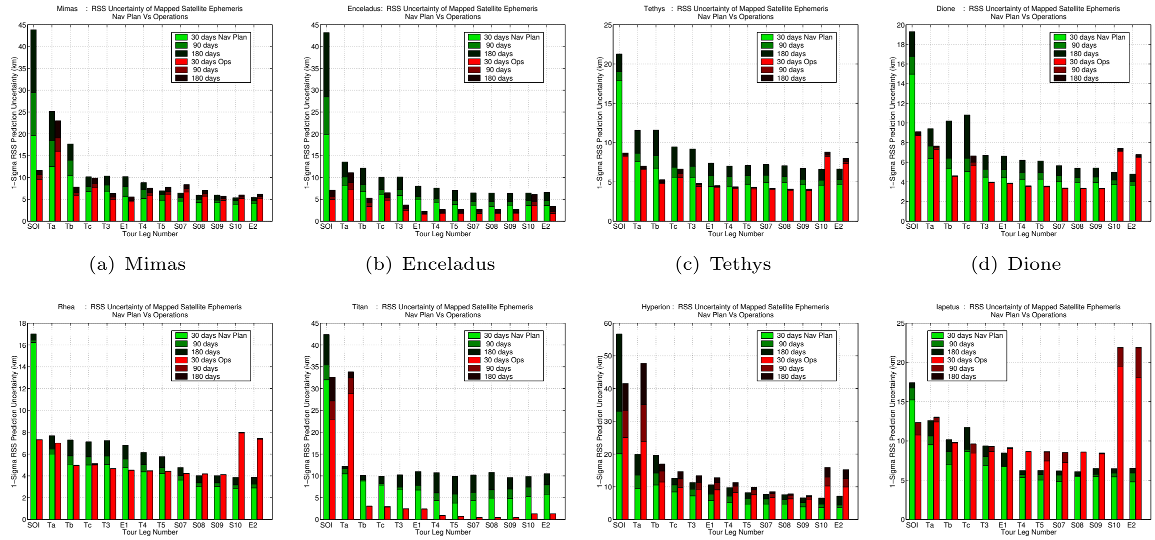


Figure 9 Encounter B-plane results (T axis lies in the Earth-Mean-Orbit plane) for the nine satellite flybys. Times are in spacecraft event time, ET (UTC + 64.2 sec)



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

(e) Rhea (f) Titan (g) Hyperion (h) Iapetus

Figure 10 Comparing the operational satellite uncertainties against Nav Plan as satellite tour progresses.

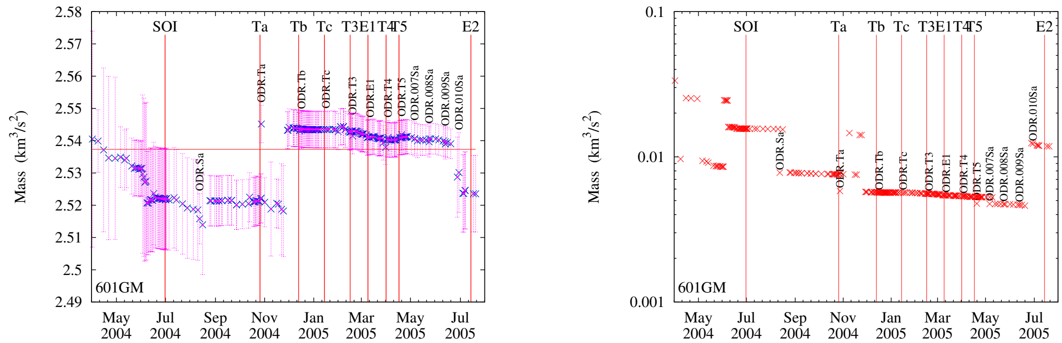
Hyperion and Iapetus. This was expected since the opnavs for these satellites have been deweighted as compared to the Nav Plan assumptions due to their center-finding difficulties. Enceladus and especially Titan show significant improvements over the Nav Plan. This can be attributed to the conservative models used in the Nav Plan. The uncertainties in the last two data arcs at the S10+ and E2+ apo epochs show significant increases for most of the moons. This is due to scaling up the satellite covariance by three prior to the E2 encounter. During this time, the scaling was applied to alleviate the concern that the satellite covariance was over constraining the OD estimates, especially for Enceladus which was the current targeted body. This was further exacerbated by the fact the optical residuals of the inner satellites, particularly Mimas and Enceladus, showed a clear negative bias (see Figure 7). As it turns out for the E2 flyby, the satellite covariance was correctly predicting the Enceladus orbit as there were little corrections to its ephemeris as a result of the flyby. This flyby helped to show that the optical data do have systematic errors. This discovery is recent and ways to mitigate these biases are being investigated.

ESTIMATION OF THE SATURNIAN MASSES

Significant improvements to the mass (GM) estimates of Enceladus, Iapetus, Phoebe, Titan and Saturn have been made through close flybys to these moons and Saturn periapsis passages. Figures 11 − 19 exhibit the improvements in the satellite mass estimates in the operational and reconstruction OD solutions as a function of time. The weighted mean value of these estimates are shown with the solid red line in these Figures. The level of improvement is indicated by the uncertainty plot in (b) of these Figures. Occasionally, the satellite covariance which at each data arc epoch represents a current fit of the data is scaled by a factor of 3 or more to reduce its constraints in the OD filter and give the more recent optical and/or radio-metric data more influence or weight on determining

Table 3 Saturn ephemeris corrections from JPL ephemeris DE410

Date of Comparison	Radial (km)	Transverse (km)	Normal (km)
July 18, 2005	-29.5 ±0.006	280.6 ±0.3	-28.4 ±6.9

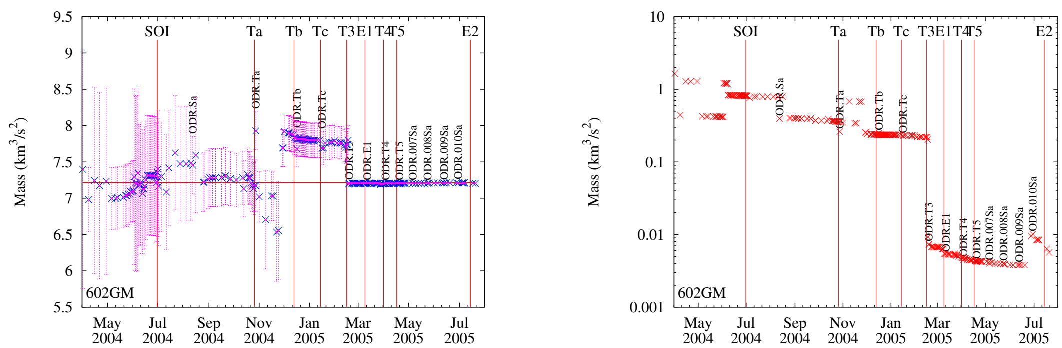


(a) Estimates

(b) Uncertainties

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

the satellite parameters. This is desired especially when multi-sigma corrections are estimated for a significant subset of the satellite parameters.



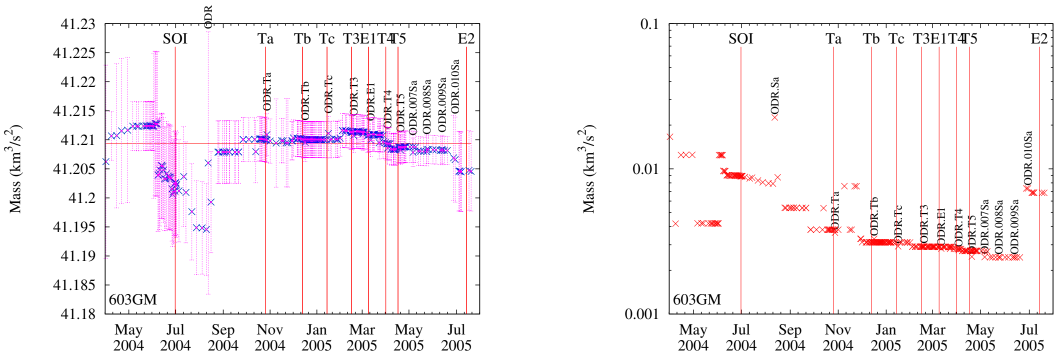
(a) Estimates

(b) Uncertainties

Figure 12 Enceladus mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

Iapetus Mass Determination

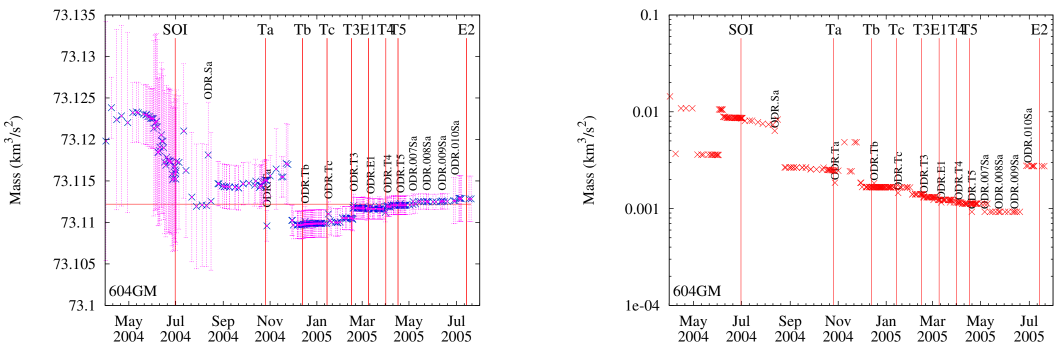
After Titan and Rhea, Iapetus is the third largest of the nine major satellites in the Saturnian system. Iapetus orbits Saturn approximately every 79 days at a mean distance of 3.56 Mkm from the Saturn system barycenter and its orbit is inclined 15.1 deg to the Saturn equator. Because of its mass and distance from Saturn, Iapetus plays a significant role in the shift of the Saturnian system barycenter from the center of Saturn. Shortly before the Huygens Probe Mission Navigation Review, it was determined that our current (post-SOI) mass estimate of Iapetus varied by more than three times its formal uncertainty. The accuracy of the Huygens probe delivery to Titan on January 14, 2005 (Tc) was dependent on the knowledge of the Iapetus mass prior to probe release on December 25, 2004 because of a close flyby of Iapetus at a distance of approximately 64,000 km subsequent to release on December 31, 2004. The flyby distance was later increased to 126,000 km to lessen the dependence on our knowledge of the Iapetus mass.[8]



(a) Estimates

(b) Uncertainties

Figure 13 Tethys mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

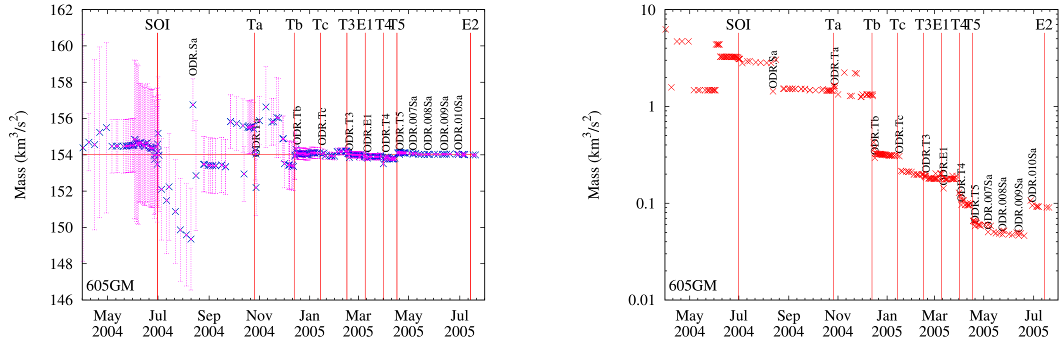


(a) Estimates

(b) Uncertainties

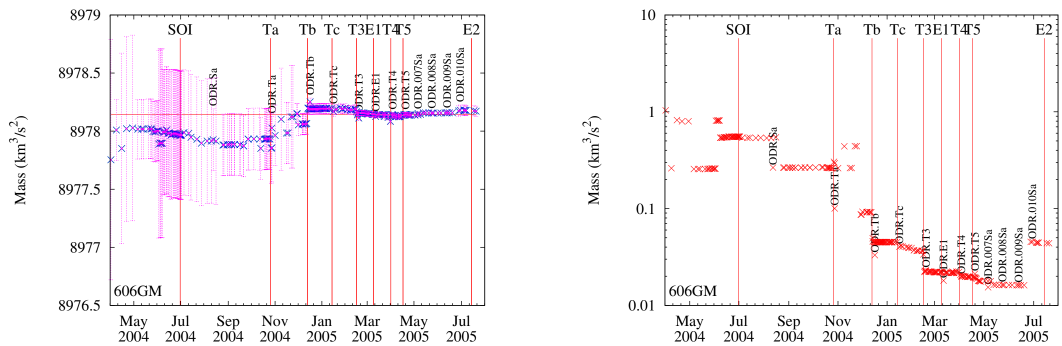
Figure 14 Dione mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

OD covariance studies showed that the Iapetus mass estimate could be improved through either direct measurements using radio-metric data before and after a close flyby of Iapetus or indirect measurements inferred through improvements in the Saturn barycenter position determination using radio-metric data before and after the first and second Titan flybys & Saturn periapses (Ta, Oct 26 and Tb, Dec 13). Prior to Cassini's arrival at Saturn, knowledge of Iapetus mass (GM) has been primarily determined using the radio-metric data through the Pioneer, Voyager 1 & 2 flybys. Prior to Cassini's Saturn insertion, the Iapetus GM value was 132 km^3/s^2 as shown in Figure 18. The formal uncertainty of this value was approximately ± 4 km^3/s^2, but lack of confidence in this number led to raising it to ± 16 km^3/s^2. Shortly after Saturn orbit insertion (SOI) on July 1st, 2004, we saw the Iapetus GM increase to $\sim$134 km^3/s^2 and then drop down to $\sim$118 km^3/s^2. The post-SOI radio-metric data was found to improve the knowledge of Iapetus by nearly 15% through better barycenter position determination. Cassini's first direct measure of Iapetus mass came after a distant 2.5 Mkm flyby on July 13th, 2004. This flyby improved the mass of Iapetus by nearly 50% relative to its formal *a priori* uncertainty. Although these determinations indicated that we had improved our knowledge of Iapetus' mass, these two events occurred during Cassini's solar conjuction period where the radio-metric data is greatly affected by the charged particles in the solar plasma. We found that a closer flyby of 1.1 Mkm would occur on Oct 18, 2004 prior to Ta. A covariance study showed that this flyby would help determine its mass significantly (below 1 km^3/s^2) especially after the radio-metric data measured its barycentric position after the Ta flyby. In addition, the



(a) Estimates (b) Uncertainties

Figure 15 Rhea mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

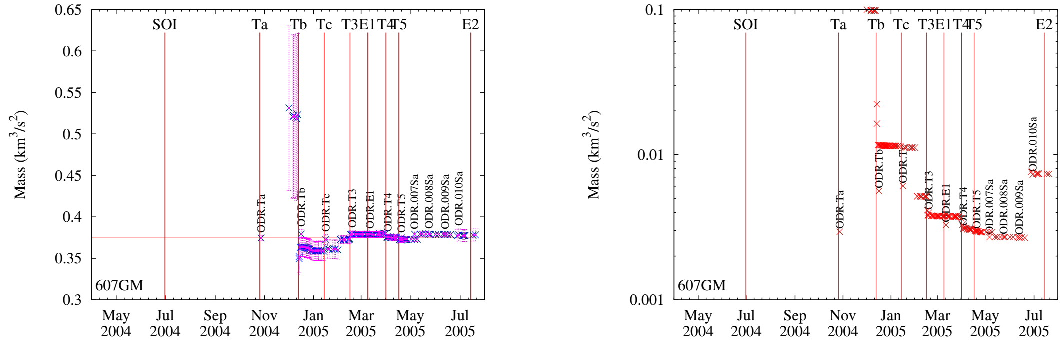


(a) Estimates (b) Uncertainties

Figure 16 Titan mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

covariance studies indicated that the Iapetus mass uncertainty would be further reduced after the Tb flyby, a result of another radio-metric measurement of Saturn's barycentric position. This time because of Iapetus' 79 day orbit it was now opposite of its position during the Ta flyby time.

To further confirm the estimates from the Oct 2004 flyby, we acquired several interferometric measurements using the National Radio Astronomy Observatory's (NRAO) Very Long Baseline Array data of Cassini. The VLBA measurement involved the differencing of several interferometric (plane-of-sky) measurements of Cassini with a galactic radio source using many baseline combinations of the NRAO radio telescopes. The measurement is similar to the ΔDOR measurement used by several recent deep space missions.[13] This VLBA technique was experimental for deep space navigation, but had already been shown with the Mars Exploration Rovers' approach to Mars to be exceptionally accurate (geometric delays < 0.10 ns). Covariance studies showed that the data acquired during the Iapetus flyby would significantly improve the Saturn barycenter in the Earth plane-of-sky frame from ± 40 km down to ± 2 km. Indeed the data did improve Saturn's barycenter to this level, however at the time of processing the data in Nov 2004, it was inconclusive in determining Iapetus' GM. Figure 18 shows that the value had settled to approximately 120.5 km^3/s^2 prior to the Huygens probe release on Dec 25, 2005. The close flyby on Dec 31, 2004 confirmed our results as we saw little change in this value.

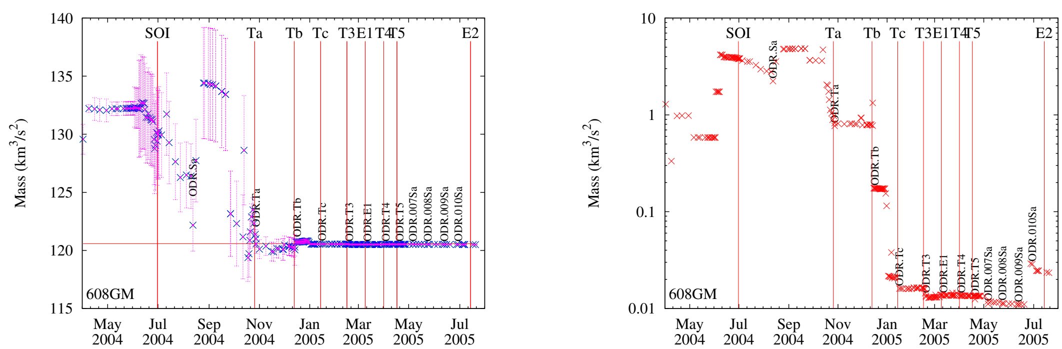


(a) Estimates

(b) Uncertainties

Figure 17 Hyperion mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

Tethys and Dione masses are well known from observations of the librations of the Lagrangian satellites, Helene, Telesto and Calypso.[15] Post-E0, E1 and E2 flyby data have determined Enceladus mass. These estimates are statistically consistent with earlier values determined solely from Enceladus resonance with the minor satellites Dione and Helene.[15] During the Ta approach it has been found that Hyperion's ephemeris has a significant effect on the determination of Titan's orbit (3:4 mean longitude resonance) even though its mass is small. The mass estimates for operation solutions showed improvements even though no close flyby of Hyperion has yet occurred and these values were much lower than scientists originally believed based on theories of its formation. Forcing Hyperion's mass to the higher assumed theoretical mass estimate had detrimental effect on OD solutions. With the latest data, all satellite masses except Hyperion have been determined to better than 1%. Given the current volumes, the densities for all satellites except Hyperion are known to better than 3%. Hyperion and Rhea are the last satellites masses to be significantly improved through flyby data. These will be improved during encounters in September for Hyperion (∼500km) and November for Rhea (500km).[16]



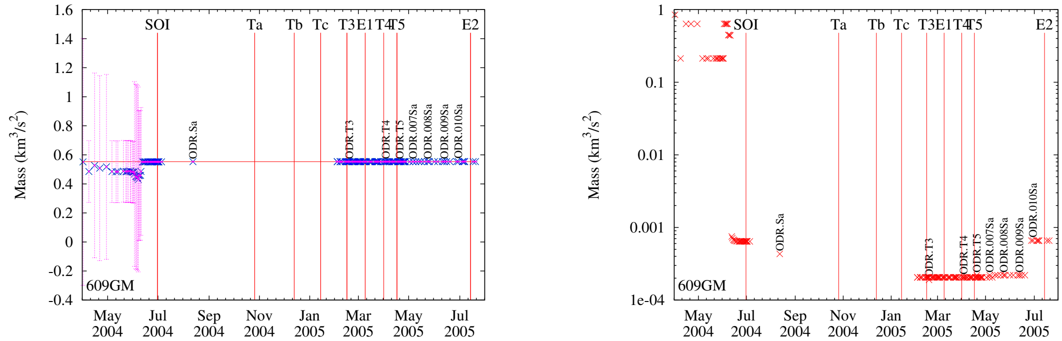
(a) Estimates

(b) Uncertainties

Figure 18 Iapetus mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

Saturn-System Mass Estimation

The evolution of the Saturn-System mass (GM6) estimates in Figure 20 show several formal sigma shifts during the course of the tour. We believe that the cause of these excursions can be attributed

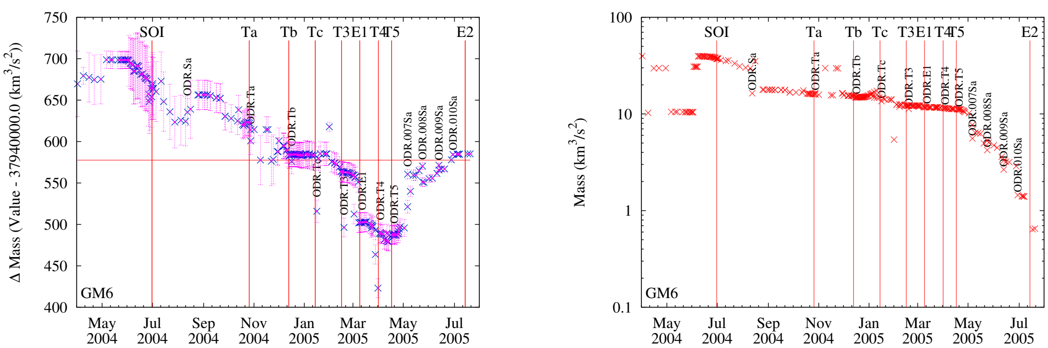


(a) Estimates

(b) Uncertainties

Figure 19 Phoebe mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

to the filter's occasional inability to distinguish maneuver and flyby induced S/C orbit changes from Saturn's gravity. Typically, the targeting maneuvers at apoapsis are fairly large but their ΔV components are not completely observable during the final approach to a flyby. Later the targeted satellite and S/C parameters, including the apoapsis maneuver, are significantly improved by the addition of the post-flyby radio-metric data in the OD filter. However, it is thought that the unknown autonomous RCS thrusting activities during the Titan flybys (Ta, Tb, Tc, etc) and atmospheric drag forces[12] could be corrupting these maneuver estimates. Between April 28 and July 8 this year during a set of 5 *empty* revs (including 4 periapse passages) the S/C experienced no close satellite flybys and minimal thrusting events. This allowed the tracking and opnav data to provide an estimate of GM6 at a previously unavailable accuracy.



(a) Estimates

(b) Uncertainties

Figure 20 Saturn System mass (GM) estimates from operational, reconstructed (labeled) OD solutions versus time.

Figure 20 shows the progression of estimates of GM6 from the end of April 2004 – July 2005. From this Figure, one can see that the GM6 estimates more or less steadily declined from the pre-SOI values by several formal sigma until about Dec 2004. A relatively large drop in this value took place in March 2005 when a new planetary ephemeris (JPL satellite & planet ephemeris SAT199) was introduced based on the powerful Very Long Baseline Array (VLBA) measurements taken of Cassini in September and October of 2004 to support the Iapetus mass determination. The VLBA data provided a direct measurement of the plane-of-sky position of the S/C which in turn contained strong information about the Saturn barycentric location normal to its orbit plane. An *a priori* correlation between this Saturn position information and GM6 caused the GM6 drop at this time. Over the course of the next few months up to the T5 flyby in mid-April 2005, a further smaller downward drift in GM6 had been observed. After T5, during the 5 empty arcs in April – July, GM6 was determined independently and its estimate increased and settled to $37,940,585.0 \pm 1.0$ km^3/s^2. We have confidence in this value but the formal uncertainty may be too constraining and should be scaled by 3.

An illustration of how the incorrect value of GM6 can affect the orbit determination was presented at the beginning of the empty rev sequence. Shortly after OTM-24 the filter estimated a large over-performance of 70 mm/s in the maneuver magnitude, this estimate did not match what was seen in telemetry. This 1.5σ variation in the maneuver parameters could fit the available data and was cheaper in terms of its effect on the estimator cost function than would be a change in GM6 by several sigma. The correlation between GM6 and the burn parameters was high shortly after the maneuver due to the dependence of the inner satellite opnavs. The inclusion of more data eventually broke down this correlation and a shift toward a maneuver estimate more in line with telemetry was seen alongside the increase in GM6.

CONCLUSIONS

The complex interaction of Saturn and the satellites and how these dynamics influence the motion of Cassini have been observed improving our knowledge of this system during the first year of the satellite tour. Significant ephemeris improvements have been made to all the major satellites, especially Titan and Enceladus due to the close flybys. All major satellite masses except Hyperion have been determined to better than 1%. These improvements have enabled better predictions of the mapped encounter conditions, especially for the T5 and E2 encounters. Careful consideration in altering filter parameter *a priori's* and data weighting must be taken so that the important information contained in the satellite ephemeris and covariance, obtained through the close flybys, is not lost.

ACKNOWLEDGEMENTS

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

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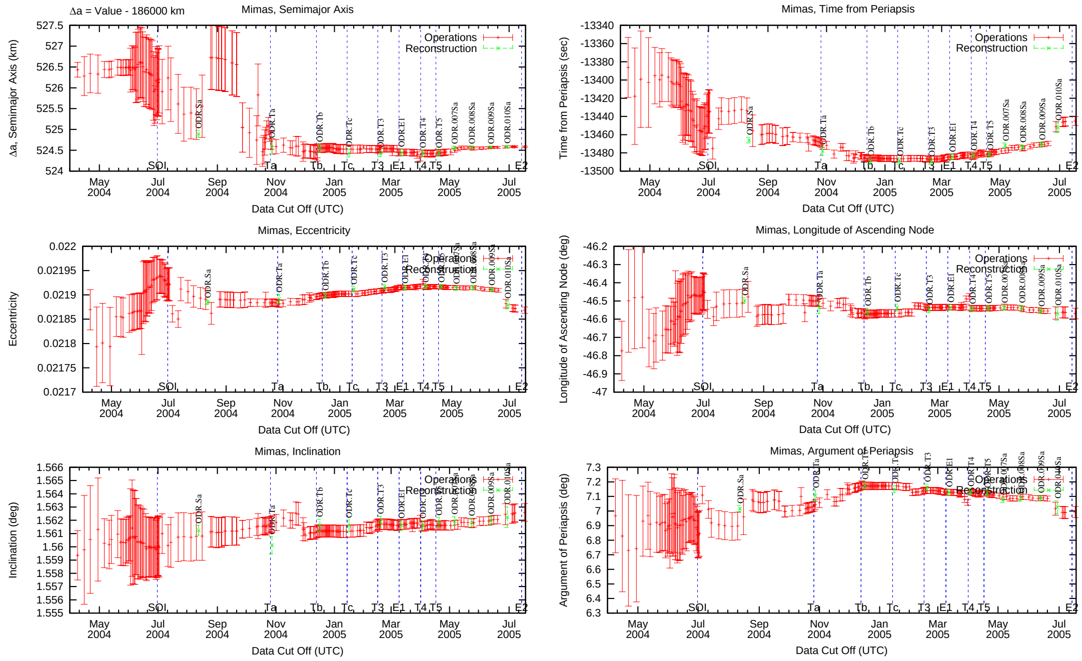
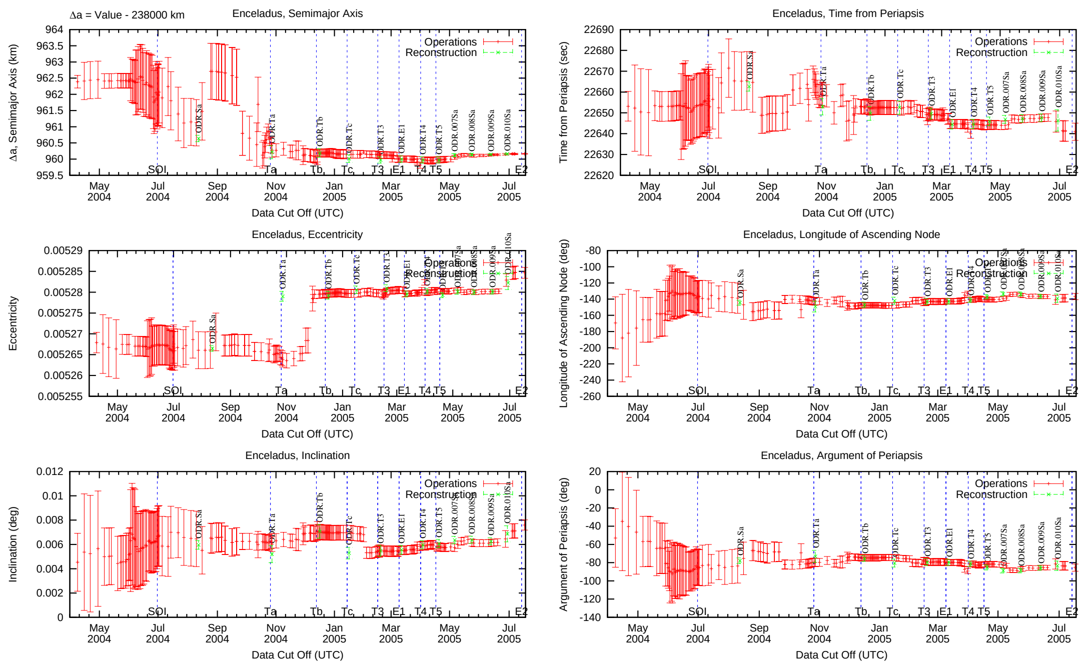
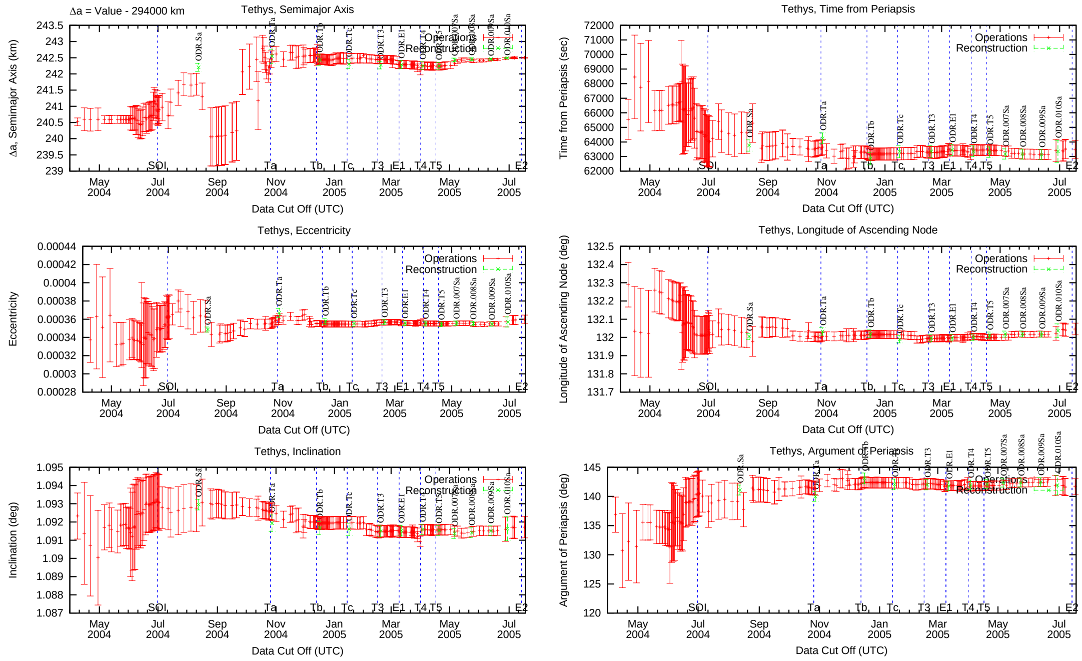


(a) Mimas

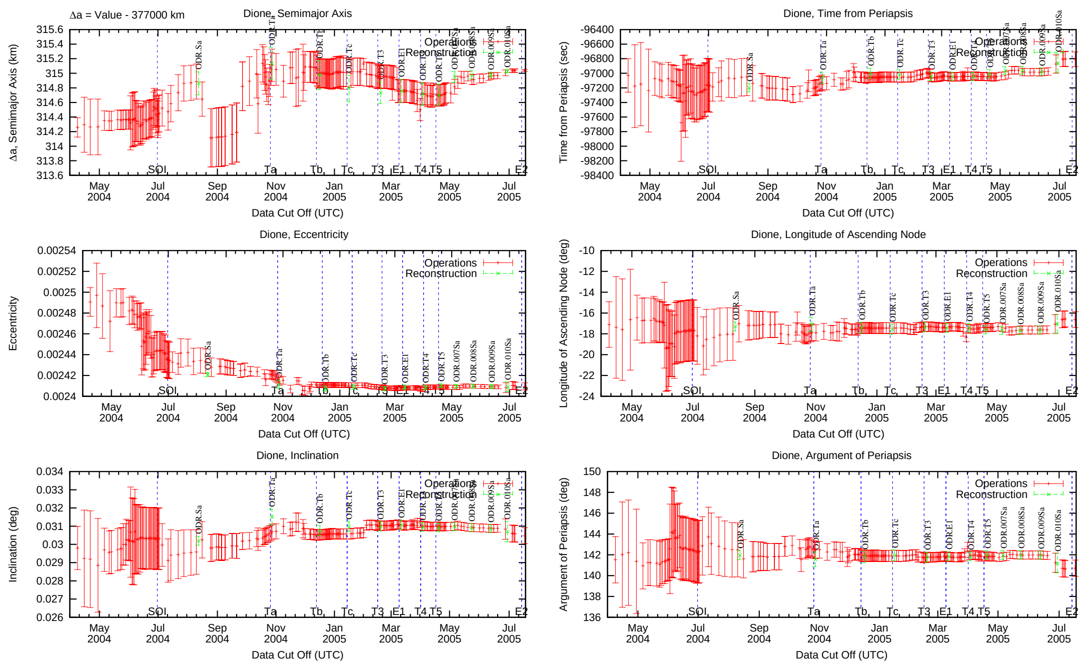


(b) Enceladus

Figure 21 Classical orbital elements of Mimas (a) and Enceladus (b) at Epoch January 2, 2004 (wrt Saturn Equator of J2000). Reconstructed values are indicated.

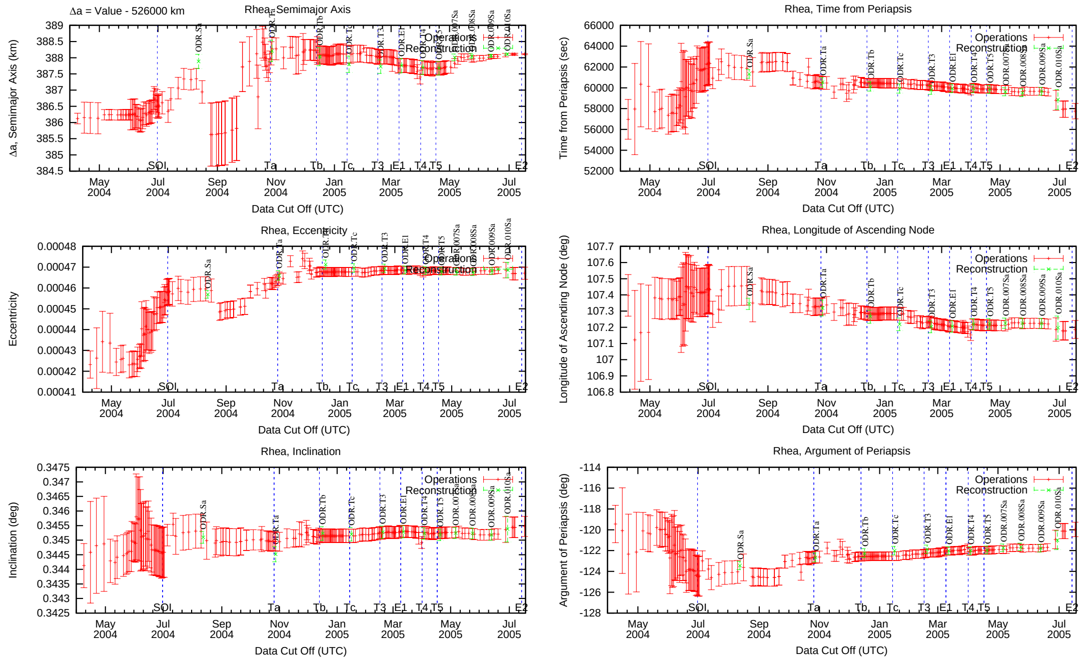


(a) Tethys

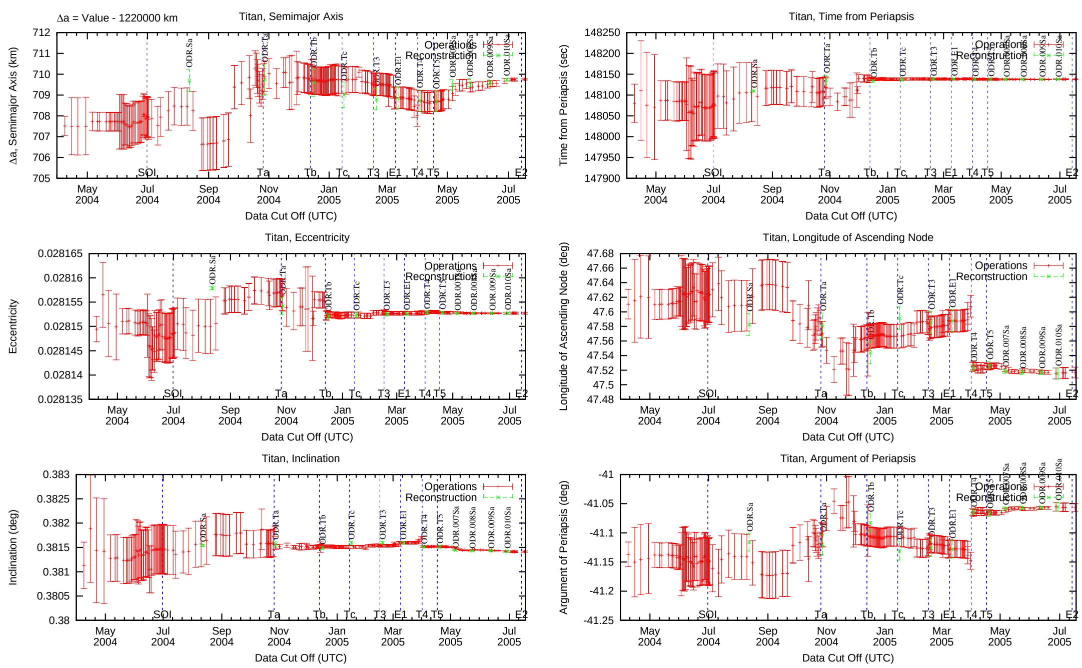


(b) Dione

Figure 22 Classical orbital elements of Tethys (a) and Dione (b) at Epoch January 2, 2004 (wrt Saturn Equator of J2000). Reconstructed values are indicated.

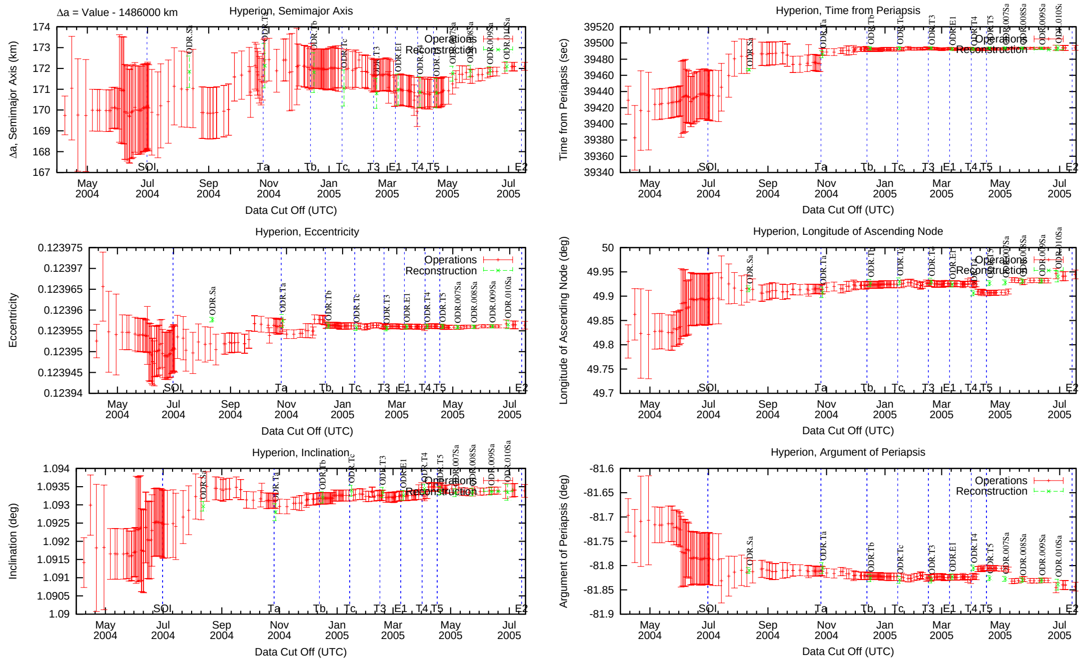


(a) Rhea

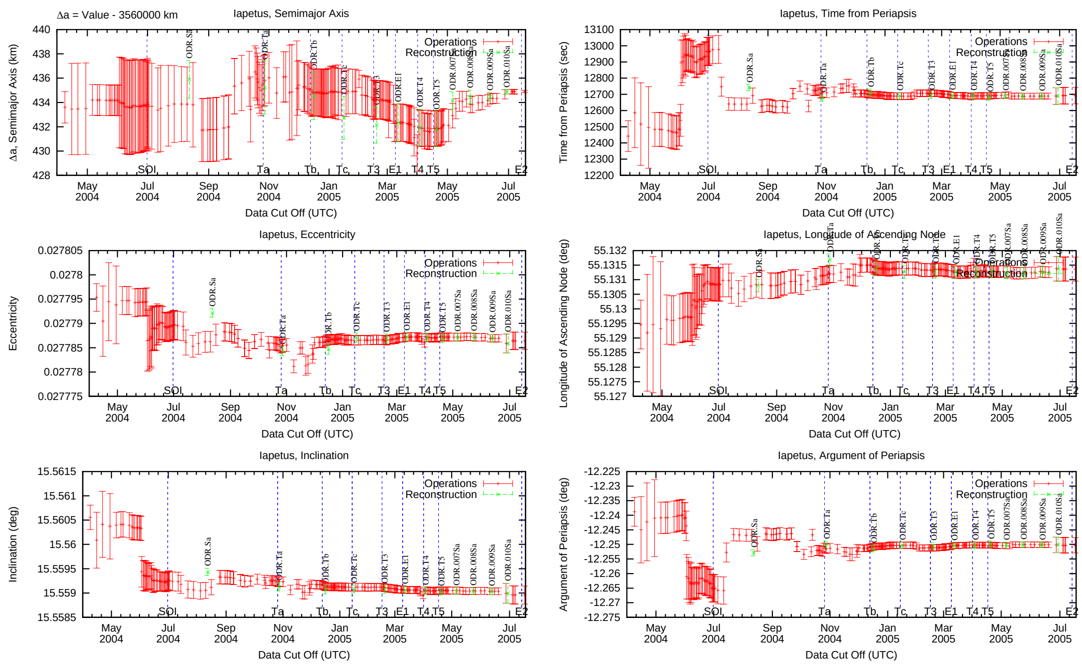


(b) Titan

Figure 23 Classical orbital elements of Rhea and Titan at Epoch January 2, 2004 (wrt Saturn Equator of J2000). Reconstructed values are indicated.



(a) Hyperion



(b) Iapetus

Figure 24 Classical orbital elements of Hypeion and Iapetus at Epoch January 2, 2004 (wrt Saturn Equator of J2000). Reconstructed values are indicated.

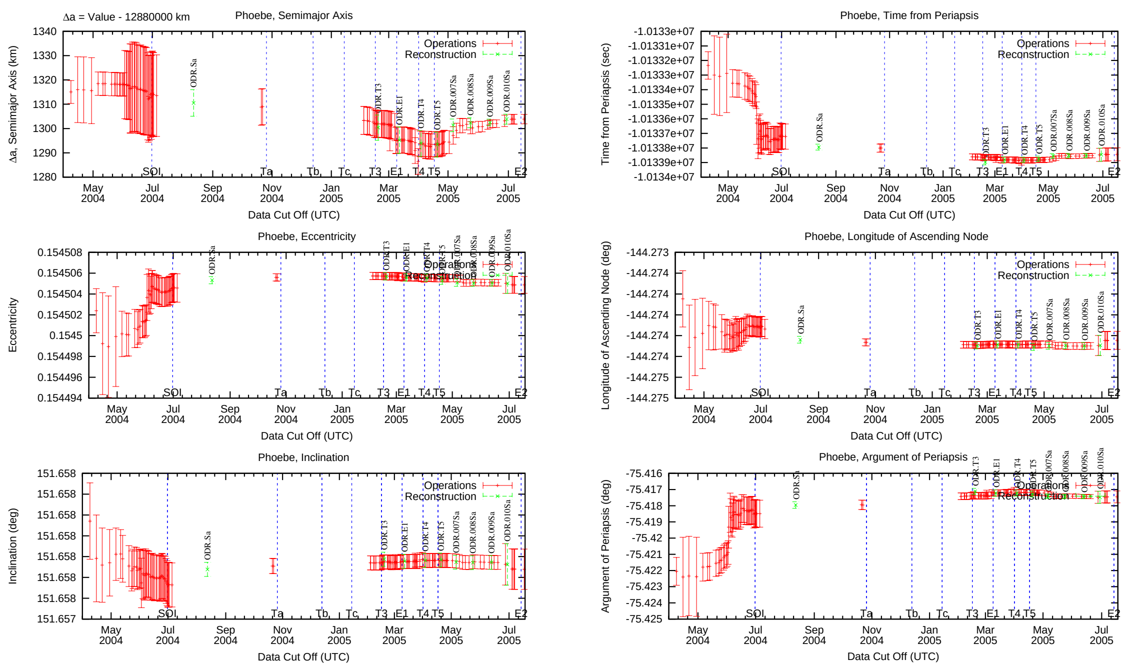


Figure 25 Classical orbital elements of Phoebe at Epoch January 2, 2004 (wrt Saturn Equator of J2000). Reconstructed values are indicated.