ORBIT DETERMINATION RESULTS AND TRAJECTORY RECONSTRUCTION FOR THE CASSSINI/HUYGENS MISSION

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ABSTRACT

During Cassini's third orbit around Saturn, the Huygens Probe was successfully released on a trajectory that resulted in the probe entering Titan's atmosphere on 14-January-2005, making it both the most distant spacecraft landing and the first spacecraft to successfully land on the moon of another planet. The navigation requirements for the probe that had to be met included the flight path angle (-65 ± 3 degrees at the 99% confidence level) and the angle of attack (0.0 ± 5 degrees at the 99% confidence level). Considering that there was no control of the probe after release and that the probe was released 21 days before landing, which was before Saturn Apoapsis and before a 123,000 km flyby of Iapetus, the most stringent navigation requirement on the probe was the flight path angle. However, the reconstructed estimate of –65.4 ± 0.6 degrees (99%) shows that the probe was delivered well within the entry angle corridor. Additional navigation requirements were imposed on the Cassini orbiter to ensure that the orbiter's pointing was accurate enough to maintain the telemetry link from Huygens to Cassini for the probe relay. The navigation contribution to this pointing error could not exceed 3.0 mrad (at the 99% confidence level). The reconstruction indicates that the maximum navigation induced pointing error during the probe relay timeframe was 1.2 mrad with a 0.03 mrad uncertainty (99%); this pointing error was increased by the decision to not update the onboard pointing parameters.

The dynamic modeling of the spacecraft, satellites, and planet, along with the measurement modeling used in the orbit determination reconstruction are described. Emphasis is placed on the unique modeling and estimation techniques required for handling the probe mission. The satellite, planet and orbiter ephemerides were reconstructed for the 24-November-2004 through 16-January-2005 time span; the reconstruction span for the probe ended at the probe interface time on 14-January-2005. These reconstructions are used as a metric against which the navigation predictions and maneuver execution errors are compared, thus providing insight into the accuracy of the operational orbit determination deliveries.

1. INTRODUCTION

This paper documents the reconstruction of both the orbiter (Cassini) and probe (Huygens) trajectories spanning the Titan-B and Titan-C encounters, which occurred on 13-Dec-2004 and 14-Jan-2005, respectively. Significant events during this orbital arc include the Titan-B flyby, a non-targeted Dione flyby, the probe release, a non-targeted Iapetus flyby, as well as the probe entry and relay that occurred during the Titan-C flyby. This paper will describe how each of these events were successfully completed from a navigation point of view and give insight into how well the operational OD used in preparing for these events performed by comparison to this OD reconstruction.

The Titan-B flyby was targeted to occur at an altitude of 1200 km on 13-Dec-2004 at 11:39:17.0 ET. From this reconstruction the flyby occurred at an altitude of 1192 km at 11:39:19.5 ET. Relative to the predicted control dispersions, the errors in the flyby were sub-sigma: 0.28 Sigma in the B-plane and 0.21 Sigma in the time of closest approach, which is equivalent to a 0.30 Sigma total error. One reason for the small size of these statistics is that the Tb approach maneuver was cancelled, so the reconstruction is compared to the OTM006 maneuver delivery dispersions. OTM006 was a large deterministic maneuver performed at the Apoapse before Tb, so the maneuver execution errors dominated the delivery ellipse.

A couple days after the Titan-B flyby there was a non-targeted 72,000 km flyby of Dione. To ensure that the spacecraft was pointed in the desired direction during this flyby, the science planning team performed a pointing update based on the OD delivery made just before the Titan-B flyby. Similarly, there was a non-targeted 123,000 km flyby of Iapetus on 31-Dec-2004 that required a pointing update based on the 15-Dec-2004 OD solution in order to meet the pointing requirements. As will be shown in a later section, the pointing errors in the OD deliveries used for these pointing updates were less than the requirements. Likewise, it will be shown that this reconstruction meets the 0.45 mrad (1-Sigma) requirement for pointing accuracy.

The probe was delivered to the interface altitude (1270 km above Titan) within all requirements (requirements

are taken from Reference 1). The achieved entry angle of –65.4 degrees (± 0.3, 1-sigma) was well within the requirement of –65.0 degrees ± 3 degrees (at the 99% confidence level). Likewise, the angle of attack requirement of zero ± 5.0 degrees (3-sigma) was met, with the reconstructed value being 1.4 degrees.

The orbiter-to-probe pointing requirements during the probe relay were also successfully met. The orbiter pointing accuracy requirement for three hours starting at the interface time was 6.0 mrad (99%). This requirement was sub-allocated between AACS (4.0 mrad) and Navigation (3.0 mrad). The maximum pointing offset resulting from the differences between the reconstructed trajectory and the reference trajectory that the onboard pointing was based on was 1.22 mrad. The maximum uncertainty in this difference was 0.01 mrad.

A listing of the significant events that occurred during this arc is given in Table 1. Additionally, the table shows the portion of the data arc that is being delivered as part of the official reconstruction to the DOM called 050214R_SCPSE_04336_05015.BSP, which includes the orbiter, probe, satellite, and planet ephemerides.

Table 1: Significant Events

Event	Date/Time
Start of Data Arc	24-Nov-2004 00:00
Start of Delivered Reconstruction	01-Dec-2004 12:00
Probe Battery Depassivation	05-Dec-2004 03:54
Titan-B Periapse	13-Dec-2004 11:38
Dione Periapse	15-Dec-2004 01:41
Saturn Periapse	15-Dec-2004 05:51
OTM008 (Probe Targeting Man.)	17-Dec-2004 01:22
OTM009 (PTM-cleanup)	23-Dec-2004 00:52
Probe Release	25-Dec-2004 02:00
Orbiter Detumble	25-Dec-2004 02:05
1st Optical Images of Probe	25-Dec-2004 14:19
2nd Optical Images of Probe	26-Dec-2004 13:41
3rd Optical Image of Probe	27-Dec-2004 13:46
OTM010 (Orbiter Deflection Man)	28-Dec-2004 00:37
Iapetus Flyby	31-Dec-2004 18:49
OTM010a (ODM-cleanup)	03-Jan-2005 23:38
Transition to RCS for Probe relay	06-Jan-2005 18:13
Probe Relay – probe interface time	14-Jan-2005 09:06
Titan-C Periapse	14-Jan-2005 11:12
Completion of Probe Relay	14-Jan-2005 12:06
End of Delivered Reconstruction	15-Jan-2005 13:00
End of Arc	16-Jan-2005 09:20

2. TRACKING DATA

The radio metric tracking schedule was such that 1 pass per day of X-band range and two-way coherent Doppler was available from the arc epoch until just before the Tb flyby. There was a gap in radio metric tracking of approximately 1.5 days during the Tb flyby, since the spacecraft was off earth point while it was collecting the various science data. For the most part, after the Dione flyby two-passes of radio metric tracking data per day were available. The exceptions to this are: a couple of days around probe separation when continuous tracking was available, around the Iapetus flyby when there was a 2 day period with only 1 tracking pass, and continuous tracking from 6-Jan-2005 until the orbiter turns toward the probe for the probe relay on 14-Jan-2005. The tracking complexes in Goldstone and Madrid provided the majority of the coverage, with Canberra tracking during periods with continuous coverage.

The Doppler and range data were weighted on a pass-by-pass basis, based on the noise in the data. The weights are assigned to be equal to the RMS of the residuals times a scale factor of 3.36. Although 1-way and 3-way Doppler data was available at various times, only one pass of 3-way data was used in the solution. This pass was used to provide coverage during the beginning of the probe battery depassivation activity, which, to remain within power allocations, involved spinning down the reaction wheels and transitioning the spacecraft to RCS control.

Optical navigation images (OpNavs) of the satellites were also processed, although there were more gaps in the OpNav coverage than normal because of the significant amount of time that the spacecraft remained Earth pointed in support of the probe mission. The first satellite OpNav was on 24-Nov-2004 05:07 UTC and the last one occurred on 27-Dec-2004 18:00 UTC. The satellites were weighted using the following algorithm:

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

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. Table 2 shows the number of OpNavs per satellite.

Table 2: Breakdown of Satellite OpNavs

Satellite	Number	Satellite	Number
Mimas	18	Rhea	21
Enceladus	12	Titan	9
Tethys	9	Hyperion	7
Dione	14	Iapetus	13

The background stars in each of the OpNav images are given a weight that is computed by taking the RSS of a minimum value of 0.1 pixels and a value that is derived from the pixel DN levels around the star.

Images of the probe taken by the orbiter in the few days after separation and before the orbit deflection

maneuver (ODM) were also successfully obtained and processed. These OpNavs were valuable in helping to provide separation between the estimates for the release ΔV and the orbiter detumble ΔV. The combination of the release and detumble ΔV's introduced a large uncertainty in the location of the probe relative to the orbiter, which made getting the first image of the probe a challenge. The first set of images was a 5x5 mosaic of wide-angle camera (WAC) pictures taken 12 hours after separation, the mosaic was taken to increase the odds of successfully capturing the probe in the images. Since the images in the mosaic have a slight amount of overlap, it turned out that the probe appears in two of the images (the center image and the next one below it). On the following day, the WAC images were processed and the increased knowledge of the probe position relative to the orbiter allowed the use of the narrow-angle camera (NAC) to image the probe. A couple of WAC images were also taken just to alleviate concerns with the instability of the operational OD solution at that time. The final probe OpNav was taken on the following day (27-Dec-2004) using the narrow-angle camera. This resulted in a total of 4 wide-angle probe OpNavs and 2 narrow-angle OpNavs. The wide-angle probe OpNavs are given a weight of 0.25 pixels, while the narrow-angle probe OpNavs are assigned a 1.00 pixel weight. The WAC images were given a tighter weight because they were on the order of 1 to 3 pixels across, which made finding the center of the image less difficult. Meanwhile, the NAC images were more extended (measuring from 5 to 9 pixels across), making it more difficult to locate the center of the image.

3. ESTIMATED PARAMETERS

Since this arc contained the probe release there are several parameters that are modeled and estimated which are unique to this reconstruction. That being said, much of the modeling and estimation schemes are very similar to what has been done in previous arcs. The main difference between this arc and others is that the trajectory of both the probe and orbiter are computed with every iteration, from the arc epoch until the end of the arc, which for the probe is only meaningful until the probe reaches the interface altitude on 14-Jan-2005. The two trajectories are forced to be identical until the time of probe release, at which point they begin to differ. To insure that the probe and orbiter trajectories are identical until release, they are initially modeled identically and all estimated parameters are applied to both models through release. The release ΔV is applied to the orbiter and probe in opposite directions, with the magnitude of the ΔV's on each body scaled by the mass ratio between the probe and the orbiter, so that linear momentum is conserved. After release, all of the usual Cassini specific acceleration models are turned off for computation of the probe trajectory. This includes accelerations that model the internally generated thermal radiation pressure, solar radiation pressure, and stochastic accelerations. Additionally, the small forces and maneuvers that occur after separation are only applied to the orbiter.

The initial conditions for the spacecraft state were interpolated from the Titan-B team's operational OD solution at the epoch of 24-Nov-2004 (close to the time of the Saturn Apoapsis between Titan-A and Titan-B). The Cartesian state of both the orbiter and probe are estimated with the a priori covariance equal to the formal covariance from the Titan-B OD solution with a data cutoff on 24-Nov-2004, scaled by 5. The internally generated thermal radiation acceleration is modeled using a constant acceleration in each of the spacecraft-fixed Cartesian directions, with each component estimated as a bias parameter. The a priori for the estimate of the internally generated thermal acceleration in the spacecraft Z-direction is the solution from the Jupiter to Saturn reconstruction (Reference 2), scaled to account for the spacecraft mass loss. Meanwhile, the a priori for the X and Y components are based off the values given in reference 3, scaled in accordance with the observed change in the Z-axis component. Acceleration due to solar pressure is modeled, however no parameters from this model are estimated. In this arc, four maneuvers were performed: the Probe Targeting Manuever (PTM or OTM008), the Probe Targeting Maneuver cleanup (PTM-cu or OTM009), the Orbit Deflection Maneuver (ODM or OTM010), and the Orbit Deflection Maneuver cleanup (ODM-cu or OTM010a). The ΔV magnitude, right ascension, declination and start time of each of these maneuvers are estimated and the results are presented in the following section. Additionally, the probe release ΔV is modeled as an impulsive maneuver for both the probe and orbiter. In the filter, the X, Y, and Z components of the release ΔV felt by the orbiter are estimated, and the release ΔV felt by the probe is forced to be equal to the orbiter ΔV multiplied by the negative of the mass ratio. This ensures that the probe ΔV is in the opposite direction as the orbiter ΔV and that momentum is conserved.

In order to account for mis-modeling of the forces acting on the spacecraft a set of stochastic accelerations are estimated in each of the spacecraft-fixed coordinates, the batch times and a priori uncertainties of these estimates vary depending on the spacecraft activity. Table 3 gives a breakdown of the stochastic batch times and the a priori uncertainties, along with a description of the spacecraft activity occurring at that time. In general, stochastic a priori uncertainties are smallest when the spacecraft is Earth-pointed and under

RWA control, and largest when the spacecraft is off Earth-point and under RCS control.

Table 3: Stochastic Accelerations

Date/Time	Batch Time	A Priori Uncertainty (X,Y,Z – km/s^2)	Description
24-Nov-2004 00:00 ET	8 hrs	3 * 1.4x10^{-12}	RWA control
05-Dec-2004 00:00 UTC	2 hrs	Z: 1.4x10^{-11}, X,Y 0.7x10^{-11}	RCS control for Probe Depassivation
05-Dec-2004 08:00 UTC	8 hrs	3 * 1.4x10^{-12}	RWA control
13-Dec-2004 07:00 UTC	2 hrs	Z: 5.6x10^{-11}, X,Y 2.8x10^{-11}	RCS control, Titan-B science pointing
13-Dec-2004 16:00 UTC	8 hrs	3 * 1.4x10^{-12}	RWA control
18-Dec-2004 20:00 ET	8 hrs	3 * 0.7x10^{-12}	Earth pointed on RWA after PTM
22-Dec-2004 16:00 ET	8 hrs	3 * 1.4x10^{-12}	RWA control (non-Earth pointed)
22-Dec-2004 20:00 ET	8 hs	3 * 0.7x10^{-12}	Earth pointed on RWA pre-separation
25-Dec-2004 00:00 ET	10 mins	Z: 5.6x10^{-11}, X,Y: 2.8x10^{-11}	RCS control for Separation activities
25-Dec-2004 06:00 ET	8 hrs	3 * 0.8x10^{-12}	Earth-pointed on RWA
31-Dec-2004 01:00 ET	8 hrs	3 * 1.6x10^{-12}	Iapetus science pointing, on RWA
01-Jan-2005 22:00 ET	8 hrs	3 * 0.8x10^{-12}	Quiet period on RWA
06-Jan-2005 17:30 ET	1 hr	Z: 20.0x10^{-12}, X,Y 1.6x10^{-12}	RCS control before probe relay
14-Jan-2005 07:30 ET	10 mins	Z: 5.6x10^{-11}, X,Y 2.8x10^{-11}	Probe relay turns for probe relay
14-Jan-2005 20:00 ET	8 hrs	3 * 1.6x10^{-12}	RWA control

RCS thrusting activities are modeled as small forces. For the small forces that are pointed in the Earth-line direction, only the ΔV magnitude is estimated, while for many of the other small forces, the right ascension, declination, and magnitude are estimated. Table 4 gives a listing of the small forces applied during this arc, including what component is estimated, a description of the event, and the source of the a priori value. During normal operations, the a priori values are predictions obtained from AACS, but for the detumble ΔV and the post-separation RCS-control dead-banding ΔV this was impossible since there were no predictions for these events. For the reconstruction, the telemetry values for the Tc-flyby RCS turns were used instead of the AACS predictions, since the telemetry values resulted in smaller stochastic acceleration estimates and helped the solution to converge.

The a priori satellite and planet ephemeris used in this reconstruction is sat198, with a data cutoff of 24-Nov-2004 applied to the covariance that is used as the a priori. The associated parameters that are included in the estimate list are given in Table 5, which includes both the a priori and estimated values and uncertainties (for states, the uncertainties are at the epoch of 02-Jan-2004).

Table 4: Small Force Summary

Date/Time	Description	A priori uncertainty
29-Nov-2004 11:28	RWA unload	Mag: 5 mm/s
5-Dec-2004 03:59 - 08:05	RWA/RCS transitions for battery depassivation	Mag: 5 mm/s
13-Dec-2004 11:17 – 12:15	RWA/RCS transitions & RCS turns for Tb	Mag: 5 mm/s
17-Dec-2004 00:54 - 01:41	RWA/RCS transitions around OTM008	Mag: 5 mm/s
25-Dec-2004 00:05	RWA to RCS transition for probe release	Mag: 5 mm/s
25-Dec-2004 01:47 - 01:53	RCS turn to probe release attitude	Mag: 5 mm/s
25-Dec-2004 02:06 - 02:13	Orbiter detumble and turn to Earth	Mag, RA, Dec: 2 mm/s
25-Dec-2004 02:24	Dead-banding ΔV	Mag: 5 mm/s
25-Dec-2004 05:21	RCS to RWA transition after separation	Mag: 5 mm/s
28-Dec-2004 00:06 - 01:01	RWA/RCS transitions around OTM010	Mag: 5 mm/s
06-Jan-2005 18:17	RWA to RCS transition before probe relay	Mag: 5 mm/s
14-Jan-2005 07:02 - 15:17	RCS turns for probe relay	Mag, RA, Dec: 2 mm/s
14-Jan-2005 20:08	RCS to RWA transition after probe relay	Mag: 5 mm/s

It should be mentioned that the reconstruction estimate for Iapetus GM of 120.54 ± 0.02 is within the uncertainty of the satellite ephemeris/covariance used during operations for this arc (sat192), which was 120.55 ± 0.79. Considerable effort was put into coming up with a good estimate for the Iapetus GM before the Tc arc, to reduce its contribution to the entry angle uncertainty for the probe. This was an issue because the Iapetus flyby occurred after the probe was released.

There are several parameters associated with the measurement models that are also estimated. A global range bias for each tracking station was estimated with an a priori uncertainty of 1 m. In addition, station range biases are estimated on a pass-by-pass basis with an a priori uncertainty of 3 m. The station locations (~3 cm uncertainty), troposphere calibrations (1 cm uncertainty), ionosphere calibrations (4 cm night & 15 cm day), and polar motion (10 cm per axis) are all considered in the filter run. Camera pointing corrections are estimated for each OpNav with an a priori uncertainty of 1 degree in each direction. Finally, Titan 0th and 1st order phase biases are estimated with an a priori uncertainty of 5%.

Table 5: Estimated Satellite and Planetary Parameters

Parameter	A priori value and/or uncertainty	Estimated value and/or uncertainty
Mimas State	± 4.00 km ± 276 mm/s	± 3.68 km ± 248 mm/s
Enceladus State	± 3.45 km ± 193 mm/s	± 3.33 km ± 190 mm/s
Tethys State	± 4.14 km ± 139 mm/s	± 3.96 km ± 134 mm/s
Dione State	± 4.49 km ± 98 mm/s	± 4.20 km ± 92 mm/s
Rhea State	± 4.37 km ± 64 mm/s	± 4.09 km ± 59 mm/s
Titan State	± 5.86 km ± 22 mm/s	± 2.73 km ± 7 mm/s
Hyperion State	± 9.99 km ± 47 mm/s	± 9.14 km ± 41 mm/s
Iapetus State	± 7.75 km ± 7 mm/s	± 7.28 km ± 7 mm/s
Mimas GM (km^3/s^2)	2.5440 ± 0.0057	2.5435 ± 0.0057
Encela. GM (km^3/s^2)	7.79 ± 0.24	7.69 ± 0.23
Tethys GM (km^3/s^2)	41.2113 ± 0.0029	41.2111 ± 0.0029
Dione GM (km^3/s^2)	73.1109 ± 0.0015	73.1110 ± 0.0015
Rhea GM (km^3/s^2)	154.20 ± 1.26	154.04 ± 0.31
Titan GM (km^3/s^2)	8978.182 ± 0.069	8978.169 ± 0.040
Hyper. GM (km^3/s^2)	0.372 ± 0.067	0.373 ± 0.061
Iapetus GM (km^3/s^2)	120.55 ± 0.35	120.54 ± 0.02
Saturn GM (km^3/s^2)	37940529.16 ± 1.42	37940515.88 ± 1.36
Saturn J2	0.0162910±0.0000014	0.0162910±0.0000007
Saturn J4	-0.0009319±0.0000065	-0.0009323±0.0000028
Sat. Pole RA (deg)	40.5753 ± 0.0021	40.5755 ± 0.0020
Sat. Pole Dec (deg)	83.5378 ± 0.0002	83.5379 ± 0.0002

4. MANEUVER RECONSTRUCTION

This section will document and compare the reconstructed maneuver estimates to the nominal designs for the four maneuvers executed during this arc, plus the separation ΔV. Two of the four maneuvers, PTM and ODM, were executed using the main engine, while the PTM-cu and ODM-cu maneuvers were executed using the RCS thrusters. Although separation did not involve the use of thrusters, it was modeled as an impulsive maneuver, so the results will be presented here. Table 6 shows the nominal design and reconstructed estimates for each of the maneuvers. It should be noted all of the maneuver estimates were sub 1-Sigma relative to the designs. The ODM-cu maneuver had the largest execution errors relative to the design dispersions. This maneuver was an overburn by approximately 4 mm/s, while the 1-Sigma uncertainty in the design was 4.4 mm/s.

The values at the bottom of Table 6 give the probe release ΔV values in EME2000 coordinates felt by the orbiter and probe, respectively during separation. The values for the probe assume a mass ratio between the orbiter and probe of 2885.61 kg / 320.00 kg. The angular difference between the design and reconstruction vectors for the release ΔV is 1.36 degrees, while the difference in magnitudes indicate that the probe felt 7.1 mm/s less ΔV in the reconstruction than the design. The a priori uncertainty used in the filter was taken from the requirement of 35 mm/s (3-Sigma).

Table 6: Nominal and reconstructed values and uncertainties

	ΔV (mm/s)	RA (deg)	Dec (deg)	Delay (sec)
OTM008				
Design	11,937.5±25.9	299.41±1.10	-78.58±0.22	0.00±10.0
Recon.	11,928.6± 5.1	299.29±0.01	-78.60±0.02	7.90±0.1
OTM009				
Design	17.6±4.1	19.98±1.40	-10.40±1.38	0.00±10.0
Recon.	20.7±1.9	19.41±1.12	-10.57±1.34	0.23±9.9
OTM010				
Design	23,785.2±48.6	199.96±0.21	7.73±0.20	0.00±10.0
Recon.	23,793.4± 3.0	200.08±0.01	7.63±0.01	8.58±0.1
OTM010a				
Design	134.7±4.4	71.16±2.34	45.61±1.64	0.00±10.0
Recon.	138.8±2.2	72.53±0.96	45.05±1.31	-0.13±3.8
		Probe Sep.		
Orbiter	X (mm/s)	Y (mm/s)	Z (mm/s)	
Design	14.8±1.3	-34.4±1.3	-1.5±1.3	
Recon.	14.0±0.5	-33.9±1.0	-2.1±0.2	
Probe				
Design	-133.3±12.0	310.4±12.0	13.3±12.0	
Recon.	-125.9±4.7	305.5±9.2	19.1±1.7	

5. TITAN-B (TB) FLYBY

The Tb flyby was previously documented in the Tb reconstruction memo (Reference 4). Although the trajectory described in this memo is the official Tb reconstruction, comparisons between the two trajectories will be made to give some insight into the consistency between the solutions. This provides something besides just the formal uncertainties as a measure of accuracy.

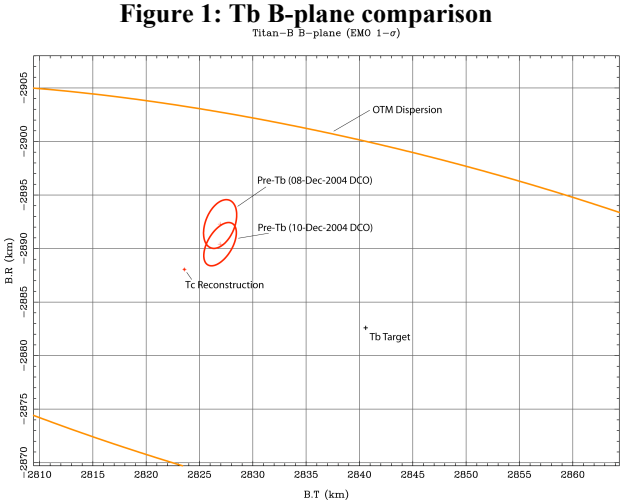
As mentioned earlier, the Tb flyby occurred on 13-Dec-2004 11:39:19.5 ET at an altitude of 1192.3 km, almost 8 km lower than targeted. Table 7 compares the B-plane values & uncertainties of the design, a couple of pre-Tb OD deliveries, and the reconstructed values from both the Tb and the Tc reconstruction memo. The first of the pre-Tb OD deliveries is from the Tb arc, this delivery had a DCO of 08-Dec-2004 05:40 and was the final official OD delivery made by the Tb team prior to Tb. It would have been the OD delivery used for the Tb approach maneuver (OTM007), if the maneuver had not been cancelled. The second pre-Tb OD delivery shown in the table was made by the Tc team using the arc being reconstructed in this memo, and although it has a

later DCO than the Tb delivery, it still provides a good comparison to the Tb team pre-Tb delivery. The final two lines in Table 7 show the two Tb reconstructed values, one from the Tb arc and the other from the Tc arc. The 1-Sigma uncertainty in altitude of closest approach for both the Tb and Tc reconstructions is 0.03 km. Figure 1 graphically shows the B-plane information presented in Table 7, although for clarity the Tb reconstruction solution has been left off the plot, since at this scale it looks identical to the Tc reconstruction of Tb.

Table 7: Tb B-plane comparison

Case	B.T (km)	B.R (km)	SMAx SMI (km)	B-plane error	Altitude (km)	TCA (sec past 11:39)
Design	2840.58	-2882.59	66.62x16.96	-	1200.00	17.00±11.7
08-Dec	2826.94	-2892.29	2.39 x 1.37	0.43	1197.64	19.22±0.26
10-Dec	2826.93	-2890.41	2.25 x 1.17	0.34	1196.29	20.18±0.31
Tb Rec.	2823.61	-2888.08	0.04 x 0.03	0.28	1192.31	19.44±0.06
Tc Rec.	2823.59	-2888.05	0.04 x 0.03	0.28	1192.27	19.54±0.08

Figure 1: Tb B-plane comparison



The primary reason for the shift in the Tb B-plane values between the pre-Tb OD deliveries and the post-Tb solutions, including the reconstructions, is a shift in the Titan state estimate. The reconstructed estimate of the Titan state differed by between 1 and 2 sigma for each of the six state parameters relative to the 10-Dec-2004 OD delivery.

6. TITAN-C (TC) FLYBY

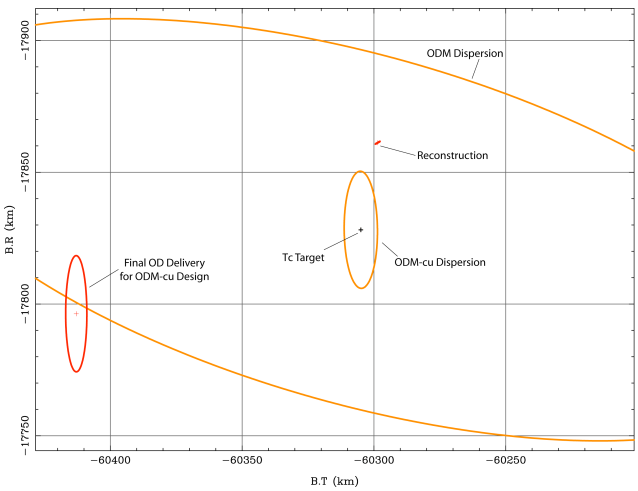
The Tc flyby occurred on 16-Jan-2005 11:13:03 ET at an altitude of 60003.3 km, a little more than 3 km higher than targeted. Tc was targeted at such a high altitude to accommodate the probe relay activities. The following section will cover the probe aspect of the Tc flyby.

Table 8 and Figure 2 compare the B-plane results for the orbiter at Tc. The first case is the ODM design, which is based on an OD delivery with a DCO on 26-Dec-2004, in the plot this is the larger of the two ellipses centered about the Tc target. The second case is the OD delivery that was used to design ODM-cu; this solution has a DCO of 02-Jan-2005. The third case shows the retargeting of the trajectory using the ODM-cu with its expected execution dispersion (based off of the same OD delivery used in the second case). The last case is the reconstruction, which as shown in both the table and plot is more than 1-sigma away from the target relative to the ODM-cu design in both the B-plane and TCA. In addition to the ODM-cu errors shown in Table 6, another reason for this shift is that there was a significant change in the ODM estimates in the OD solutions after the ODM-cu design DCO. The Right Ascension and Declination values for ODM changed by approximately 1.4 sigma and the V magnitude estimate changed by about 0.7 sigma, relative to the final ODM-cu design OD solution estimates. Other greater than 1-sigma differences relative to the ODM-cu design OD delivery and the reconstruction are in some of the small forces events that modeled detumble and other activities just after separation. It should be noted that the operational OD solutions that were made after ODM-cu slowly began moving towards the reconstruction estimates, so if these B-plane solutions were shown on Figure 2, a trend from the Tc target towards the reconstruction would be apparent. One value of interest, but not shown not shown in Table 8 is the 1-Sigma uncertainty in the Tc altitude, which is equal to 0.70 km in the reconstruction.

Table 8: Tc B-plane comparison

Case	B.T (km)	B.R (km)	SMAxSMI (km)	B-plane error	Altitude (km)	TCA (sec past 11:13)
ODM Design	-60304.98	-17828.17	179x66	-	60000.0	0.0±35.5
ODM-cu OD	-60412.92	-17796.30	22.1x4.0	1.1	60094.5	19.8±2.8
ODM-cu Design	-60304.98	-17828.17	22.2x6.3	-	60000.0	0.0±2.9
Recon.	-60298.57	-17861.23	1.03x0.09	1.8	60003.3	3.0±0.1

Figure 2: Tc B-plane comparison



7. THE PROBE RESULTS

Rather than B-plane parameters the probe targeted an entry angle of –65.0°, an altitude of 1270 km, and a B-plane angle of 167.5° at the interface time of 14-Jan-2005 09:07:00 ET. Both maneuvers before separation (PTM and PTM-cu) targeted these parameters. The most stringent requirement to meet from an OD standpoint was the 99% entry angle corridor of 65.0° ± 3° (approximately equivalent to ±1.15° in a 1-Sigma sense). Table 9 shows how the entry angle and interface time values and uncertainties changed from PTM through the ODM-cu OD delivery and finally the reconstruction.

Table 9: Entry Angle and Interface Time Estimates & 1-Sigma Uncertainties

Case	Entry Angle (deg)	Interface Time (ET)	Uncertainty (sec)
PTM Design	-65.00 ± 9.69	14-Jan-2005 09:07:00.00	136.72
Final PTM-cu OD delivery	-63.76 ± 0.41	14-Jan-2005 09:06:55.44	6.92
PTM-cu Design	-65.00 ± 0.89	14-Jan-2005 09:07:00.00	13.92
Final pre-separation OD	-65.33 ± 0.81	14-Jan-2005 09:06:55.45	12.57
Final ODM OD delivery	-65.65 ± 0.70	14-Jan-2005 09:06:49.97	15.87
Final ODM-cu OD delivery	-65.31 ± 0.29	14-Jan-2005 09:06:58.54	6.16
Reconstruction	-65.40 ± 0.27	14-Jan-2005 09:06:56.71	5.82

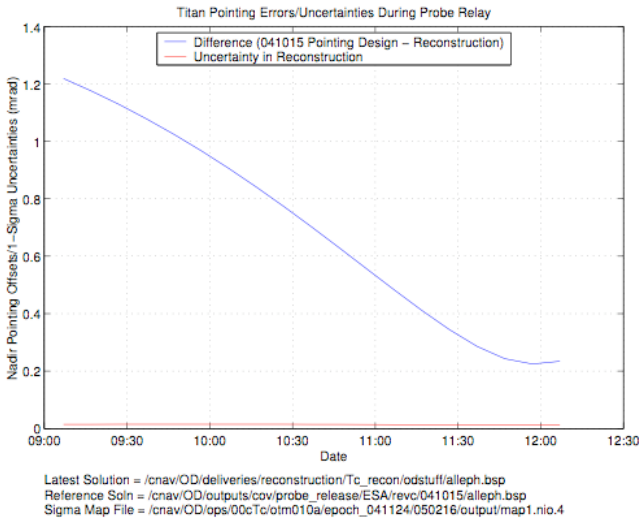
Note that the uncertainties in the final PTM-cu OD delivery are so low because they do not include the uncertainty of separation. From the first two lines, the entry angle estimate of –63.76 after PTM was well below the 1-Sigma control dispersion for the PTM design.

Note that the entry angle uncertainty did not drop more significantly and the interface time uncertainty rose between the final pre-separation OD delivery and the final ODM OD delivery. This is a result of the a priori separation uncertainty being scaled by three immediately following the probe release because of some confusion with the AACS reconstruction of the separation ΔV, which was quite a bit different than the design. When enough post-separation tracking became available, we became confident that the separation ΔV was actually fairly close to the design and the scale of three was removed from the a priori uncertainty on the separation ΔV. Also from Table 9, the difference between the PTM-cu design and the reconstruction is well below the 1-Sigma control dispersions for both the Entry Angle and the Interface Time.

From the reconstruction results, it is clear that the probe was well within the entry angle corridor. Additionally, the other targets were within the requirements. The B-plane angle was equal to the targeted value of 167.5°. The angle of attack, although not explicitly targeted, was desired to be within 5° 3-Sigma of 0°, it turned out to be equal to 1.44° (Reference 5).

Another requirement for the probe mission was for the orbiter to maintain a minimum pointing accuracy of 6 mrad (99%) during the probe relay timeframe, which was defined as three hours starting at the interface time. The 6 mrad accuracy level was split into an AACS allocation and a Navigation allocation, the Navigation allocation was determined to be 3 mrad (99%). The onboard pointing parameters were designed based on the 041015 covariance study delivery (made on 15-Oct-2004). The plan was to use ODM-cu to get the spacecraft relative to Titan trajectory back close to this reference, rather than updating the pointing parameters. Figure 3 shows the difference in the pointing between the 041015 design and the reconstruction as well as the pointing uncertainties in the reconstruction during the probe relay time. The uncertainty in the reconstruction pointing errors (the red line) are small enough that the blue line approximates the amount of pointing error due to the OD used to design the pointing parameters. Since the maximum error during the probe relay timeframe is 1.2 mrad, the 3 mrad Navigation probe relay pointing requirements were met.

Figure 3: Relay Pointing Errors and Uncertainties



8. POSITION AND POINTING UNCERTAINTIES

Figure 4 shows the position uncertainties for the Orbiter during the Tc arc relative to the Saturn Barycenter. As usual, the largest uncertainties occur near Saturn apoapse, while the trajectory is known best near Saturn periapse.

A pointing update was needed to ensure that the spacecraft would be pointing at the desired location for the Iapetus flyby on 31-Dec-2004. Figure 5 compares the OD solution used for the pointing update (041215_00cTc) with the reconstruction. From this plot, it is clear that the 041215 OD delivery met the accuracy requirements for Cassini pointing to Iapetus during the flyby.

Figure 4: Cassini Position Uncertainties Relative to the Saturn Barycenter

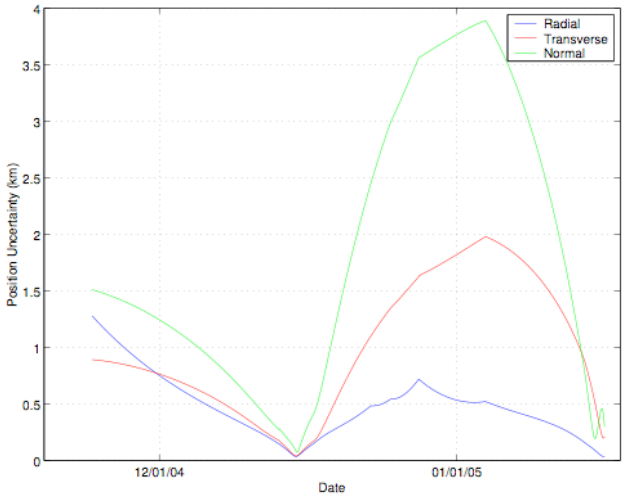
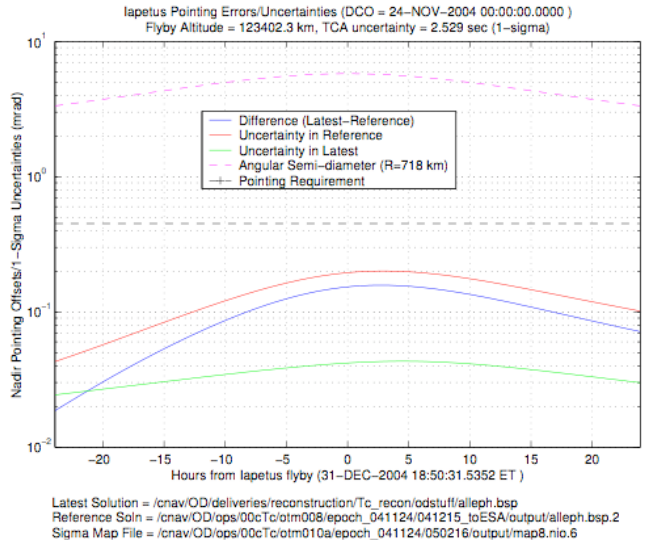


Figure 5: Cassini to Iapetus pointing errors



9. CONCLUSIONS

The Navigation goals for the Tc arc were all successfully met. This includes the pointing requirements for the Iapetus flyby, the delivery of the probe within the target constraints, and delivering the orbiter accurately enough to meet the probe relay pointing requirements. Execution errors for all maneuvers were sub-Sigma, although the Tc flyby was outside the 1-Sigma control dispersions for the ODM-cu maneuver. The reasons for this include greater than 1-Sigma shifts in both the ODM solution (relative to the ODM-cu design OD delivery) and in some of the small forces just after separation. Additionally, ODM-cu itself was almost a 1-Sigma over burn.

10. REFERENCES

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