Presentation

MANEUVER-TARGETING STRATEGIES AND RESULTS FOR THE CASSINI-HUYGENS MISSION

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ABSTRACT

The Cassini-Huygens mission delivered the Huygens probe to Saturn's moon Titan on January 14, 2005. It became both the most distant landing of a spacecraft and the first spacecraft to successfully land on the moon of another planet. This first stage of the mission, the landing, required a 99% confidence on achieving an entry-angle between -62° and -68° with -65° as the mean. Although this was the most stringent requirement on navigation, there were also requirements on the time to reach the defined interface altitude, B-plane angle, angle of attack, and V_∞. These requirements were primarily achieved via two probe-targeting ΔV maneuvers executed after the previous flyby of Titan.

In the second stage of the mission, the orbiter needed its trajectory adjusted to achieve the proper Titan-flyby geometry for reception of the data from the Huygens probe. This geometry was achieved by targeting B-vector magnitude, B-plane angle, and time of closest approach. However, the large shift from an impacting trajectory to a 60,000 km flyby also required a clean-up maneuver to achieve the necessary accuracy for probe-relay pointing.

In addition to these challenges, all four ΔV maneuvers and the separation event, which also imparted a ΔV, had to be designed, analyzed, and executed during the 32-day period between Titan flybys. Achieving that schedule required detailed upfront analysis and development of specialized tools to automate repetitive tasks such as updating maneuver designs with the latest orbit determination and computing performance data of those designs.

Maneuver-targeting strategies, including navigation analysis performed prior to the probe mission, and trajectory-control performance results seen during that mission are described. Discussion of maneuver scheduling and descriptions of software tools are also provided. Navigation analyses are summarized; these were focused on statistical modeling of targeting strategies, maneuver execution errors, and orbit determination errors to compute probe and orbiter delivery errors. Results from the orbit-determination reconstruction are compared against predictions to measure the performance of the maneuver strategies and execution-error modelling.

Key words: Cassini, Huygens, Saturn, Titan, navigation, maneuver, targeting.

1. INTRODUCTION

1.1. Trajectory Design

The Cassini-Huygens spacecraft arrived at Saturn and performed the Saturn Orbit Insertion (SOI) burn on Saturn on July 1, 2004. In the initial tour trajectory, T18-5, developed before launch of Cassini-Huygens, the probe mission would occur on the orbit following SOI, the first around Saturn[1, 2].

In February 2000, a probe checkout test discovered that the bit synchronizer of the Huygens receiver onboard the Cassini orbiter could not accommodate the Doppler shift of the relay signal. Shortly thereafter, an ESA independent enquiry board formed the joint ESA/NASA Huygens Recovery Task Force (HRTF) to resolve the issue [3]. The tour at Saturn was altered to reduce the Doppler shift between the orbiter and probe during the data relay period.

The new tour, T2002-01[4], would arrive at the first Titan flyby 32 days earlier than in T18-5 and allow time to insert an extra 32-day orbit after a distant flyby (Tc) and still return to the T18-5 tour by the T3 flyby. In this scenario, three new Titan flybys replaced the first two Titan flybys of T18-5. In order to avoid the confusion of renumbering all of the flybys in the rest of the tour, the first three flybys of the new tour were renamed to Ta, Tb, and Tc. The probe would be delivered on the Tc flyby in tour T2002-01 (Fig. 1).

1.2. Mission Timeline

Often, the probe mission is referred to as occurring in a few hours, but from the perspective of the navigation team, the mission encompassed the entire trajectory leg

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Table 1. **Timeline of Mission Events** *T-rel. indicates Titan-relative timing, in days. TA indicates true anomaly, in degrees, for the Saturn-relative orbit—at this precision, the same value is seen for probe and orbiter. This data has been updated from the navigation plan [5, 6] to more closely reflect the actual mission.*

Event	T-rel.	Date (SCET-UTC)	TA	Comments
Titan-b flyby	Tc-32	13-Dec-2004 11:38	-126°	1,200 km altitude
Pericrone	Tc-30	15-Dec-2004 05:51	0°	
PTM	Tc-28	17-Dec-2004 01:22	131°	Target to Probe entry
DCO for SEP	Tc-23	22-Dec-2004 03:30	161°	
PTM-CU	Tc-22	23-Dec-2004 00:52	163°	Target to Probe entry
Probe separation	Tc-20	25-Dec-2004 02:00	169°	
ODM	Tc-17	28-Dec-2004 00:37	174°	target Orbiter, achieve delay time (ODT)
Apocrone	Tc-14	31-Dec-2004 04:35	180°	
Iapetus flyby	Tc-13	31-Dec-2004 18:49	-179°	127,000 km flyby distance , not targeted
DCO for entry sequence	Tc-12	2-Jan-2005 03:00	-177°	support uplink telemetry from Probe
ODM-CU	Tc-10	3-Jan-2005 23:38	-174°	reestablish pointing profile, ODT
Probe entry, interface alt.	Tc	14-Jan-2005 09:07 ET[a]	-133°	1,270 km altitude
Orbiter-Titan Periapsis	Tc	14-Jan-2005 11:13 ET[b]	-133°	60,000 km altitude

[a]ET is listed here as the maneuver target value was in ET
[b]ET is listed here as the maneuver target value was in ET

from Titan-b to Titan-c. Orbit Determination (OD) analysis and a string of maneuvers across this entire leg were necessary to achieve the requirements. Herein, the term "probe mission" refers to the trajectory arc leading up to delivery of the probe to the interface altitude and ending with the Orbiter's flyby of Titan at the Titan-c encounter.

Typically, Cassini-Huygens' tour orbits are marked by three ΔV maneuvers: a clean-up maneuver about three days after a satellite encounter, a shaping maneuver near apocrone, and a final-targeting maneuver about three days before the next satellite encounter. The encounters that defined the trajectory leg of the probe mission were the Titan-b and Titan-c encounters. These encounters and other relevant events are listed in Table 1.

After the Titan-b flyby on 13 December 2004, the combined Cassini-Huygens spacecraft was targeted to the Probe target specified by ESA. Twenty days before Titan-c, the Huygens Probe and the Orbiter separated from each other; there were no further opportunities to correct the probe's course. Three days later the Orbiter performed a large deflection maneuver in order to move off the impact trajectory and delay arrival so that it arrived 2.1 hours after the Probe. The Probe entered Titan's atmosphere on 14 January 2005 as the Orbiter continued by Titan; it received and recorded telemetry as the Probe descended through the atmosphere and impacted the surface. The Orbiter flyby altitude was 60,000 km.

Herein, the first stage of the mission refers to the period from the Titan-b flyby to probe entry (reaching the interface altitude). The second stage refers to the orbiter's events from separation through the probe-relay sequence. The terms *probe* and *orbiter* are used when they are separated from each other, while the term *spacecraft*, or combined spacecraft, is used to refer to the two attached together.

In general, maneuvers were placed [7] as early as possible while meeting requirements. The sequence of maneuvers for the probe mission was Probe Targeting Maneuer (PTM), Probe Targeting Maneuver Clean-up (PTM-CU), probe separation (SEP), Orbiter Deflection Maneuver (ODM), and Orbier Deflection Maneuver Clean-up (ODM-CU). These five maneuvers did not fit the three-maneuver pattern described above: PTM had a large, deterministic ΔV component to place the probe on a Titan-impacting trajectory while ODM also had a large, deterministic component to put the orbiter on a Huygens-relay flyby of Titan. The respective clean-up maneuvers lacked deterministic components by design, holding out the possibility that one or both might not be needed. The maneuver locations are depicted in Fig. 1.

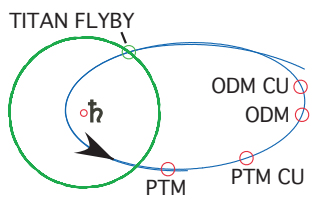

Figure 1. **Trajectory for Titan-b to Titan-c.** *Only Saturn, Titan's orbit, spacecraft's orbit, and maneuver locations are shown*

1.3. Navigation Strategy

The prime concerns in navigation for the probe delivery were robustness and reliability. Robustness was achieved

by scheduling maneuvers and separation as early as possible. Unanticipated delays in separation and/or maneuver executions could be accommodated within the same orbit by shifting activities downstream. Reliability was achieved by delaying the OD Data Cut-Off (DCO) used for maneuver designs by one day beyond the day for which probe relay accuracy requirements were first met. Delaying the OD DCO limited vulnerabilities to tracking data losses and increased confidence in orbit solutions. The planned maneuver locations would provide sufficient time to reconverge the trajectory estimate after each maneuver, allow for a backup or recovery maneuver in the event of a problem, and only require a reasonable amount of propellant.

2. REQUIREMENTS

Requirements on navigation for the probe mission are documented [8]. Only those most influential to the probe-navigation strategy are included here.

The interface altitude of 1270 km defined a point well outside the atmosphere of Titan where JPL's responsibility for orbit propagation ended and ESA's responsibility began. This was the altitude at which the "entry angle" was defined, although it should be understood that the actual atmospheric entry was at a considerably lower altitude. The time at which the nominal Probe trajectory crossed the interface altitude was defined as the interface time.

The required interface time for the primary Huygens mission was 09:07 ephemeris time (ET) [9] on 2005 January 14. At this time and altitude, other requirements were set. The entry angle requirement was -65° +/-3° at the 99% confidence level, in the Titan body-fixed frame. This was referred to as the entry-angle corridor.

The angle-of-attack, α, requirement was stated as: [8, p.30,36-37]

> The orbiter shall deliver the probe at a nominal attitude corresponding to a zero angle of attack, with requirement to be below 5 degrees at 1270 km altitude.

The requirement of 5° was at the 3-σ level. The requirement also stipulated that the aeroshell symmetry axis of the spinning Probe must be in parallel opposition the Titan-centered Probe velocity vector at the interface altitude.

The B-plane angle ϕ, described in Section 8, at the interface altitude was required to nominally be 167.5° in a B-plane coordinate system relative to Titan's equator of date.

The B-plane angle for the orbiter's flyby was required to nominally be at 180°. The flyby altitude for the Orbiter was to be 60,000 km.

Table 2. **Mission Parameters** *shown as planned in the reference trajectory, as predicted for maneuver design, and error reflected by OD reconstruction (err = est - predict)*

	Ref. Traj.	Predict	Est. Err.
interface time[a]	09:07	09:07	-3.29 s
Probe V_∞[b], km/s	5.63	5.63	0.8 m/s
Probe B ang, deg	167.5	167.5	0.015
entry ang, deg	-65	-65	-0.4
AOA, α, deg	0	0.09	1.4
Orbiter alt., km	60,000	60,000	3.3
Orbiter TCA[c]	11:13	11:13	3.0 s
Orbiter B angle, deg	-180	-180	0.03

[a] on January 14, 2005, in ET
[b] not a target, but is a parameter of interest
[c] at closest-approach, January 14, 2005, ET

The Orbiter Delay Time (ODT) was the length of time between the interface time and the orbiter's periapsis with Titan. The ODT was set at 2.1 hours and the Orbiter flyby closest-approach would be nominally at 11:13 ET on January 14.

OD estimates wouldn't achieve the pointing-relay accuracy until 5 days after ODM. With that accuracy, either the Cassini Orbiter's on-board pointing profile could be updated or a maneuver could be executed to recover the nominal pointing profile. That maneuver would be ODM CU; as listed in Table 1, it existed only to satisfy pointing requirements during probe relay; an update to onboard parameters could have rendered it moot. However, the project found that the effort to produce and review for accuracy a pointing update was less favorable than the well-understood practice of designing and implementing a maneuver.

3. TARGETING

Three kinds of targeting were used for maneuvers of the Huygens mission. PTM and PTM-CU targeted parameters, like entry angle, directly. SEP had a fixed design, determined before the Titan-b flyby. ODM and ODM-CU used B-plane targeting.Values used for the targeted parameters are listed in Table 2.

Target parameters for PTM and PTM-CU, determined at the epoch of the interface time (t), were altitude (h), B-plane angle (ϕ), entry angle[1] (γ), and angle of attack (α). The altitude and B-plane angle are computed with respect to the inertial reference frame and the Titan Equator of Date coordinate system (defined in Section 8). The altitude target for PTM and PTM-CU was the interface al-

[1] The entry angle is sometimes defined with a sign convention that's negative of flight-path angle's, but for this mission, entry angle and flight path angle have the same sign convention so that both are typically negative numbers

titude. The angle-of-attack was computed in the inertial reference frame; making the assumption that the separation ΔV, the probe's axis of symmetry, and the probe's angular momentum vector are aligned, it was taken to be the angle between the separation ΔV as felt by the probe and the Titan-relative velocity of the probe at the interface time (in the inertial reference frame). The separation ΔV was assumed to be aligned with the spacecraft's x-axis, which was nominally parallel to the probe's axis of symmetry while attached to the orbiter.

The entry angle, γ, was unique among the targets in that it was computed with respect to the Titan body-fixed reference frame. For the Huygens mission, the inertial entry angle was only about 0.15° different from the value using this definition.

When computing ΔVs to achieve the PTM and PTM-CU targets, a trajectory propagation of the probe was used. The modeling for this would include the separation event and the loss of the orbiter's mass. For example, models for Attitude and Articulation Control Subsystem (AACS) Reaction Control Subsystem (RCS) thruster firing were not included for the probe trajectory. In this way, PTM and PTM-CU would target only the probe trajectory, not the combined spacecraft, to the prescribed conditions at the interface altitude.

Similar consideration was given to the ODM and ODM-CU targets. In this case, separation and mass loss were modeled prior to the maneuver. The result was similar in that ODM and ODM-CU would target only the orbiter trajectory to the prescribed Titan-c flyby conditions.

PTM, like PTM-CU, was designed in conjunction with SEP for the reference trajectory. If designed independent of separation, then the targeted angle of attack would not be zero. It would be nonzero because neither PTM nor PTM-CU would have enough flexibility to target a fourth parameter. In order to satisfy all targets for probe entry, the PTM and SEP ΔVs must be designed together. In doing so, there are 6 independent variables (3 per ΔV), 4 targets, and a constraint on the magnitude of the SEP ΔV. The one remaining degree of freedom is the orientation of the spacecraft around the separation ΔV direction. The spacecraft may be rotated about the separation ΔV direction by any angle without affecting any target parameters.

Designing these maneuvers together was feasible and desirable for the reference trajectory because the reference was made well in advance of the mission and used for planning purposes. However, in the midst of mission operations, the simplicity of designing maneuvers individually was seen to be superior.

In operations, the SEP ΔV was designed and 'put on the shelf' prior to the probe mission. When designs were made for PTM and PTM-CU, the predesigned SEP was modeled and angle of attack was not targeted. As may be seen in Table 2, the angle of attack that resulted from the operational maneuver designs was non-zero. However, it was small enough to remain within requirements so that the more complicated approach of designing two maneuvers together was not needed. By designing SEP in advance, the spacecraft command sequence file that contained it was not altered, saving the project the work of having to re-check it for errors.

The separation ΔVs as felt by the probe and by the orbiter were taken from probe-separation simulations [10]. In Navigation's analysis, the two ΔVs were in opposing, parallel directions. The direction was determined as described earlier. The magnitude of the probe-relative separation ΔV was taken from the simulation and the magnitude of the orbiter-relative separation ΔV was computed by conservation of momentum.

4. MANEUVER SCHEDULING

The entry-angle and relay-pointing requirements were very important for the layout of the maneuvers for the probe mission. The entry-angle requirement determined the placement of the PTM-CU and the relay-pointing requirement determined the placement of the ODM-CU. With these two in place and the desire to mitigate risk to the schedule by placing events as early as possible[2], the timeline of the probe mission was largely determined.

PTM-CU was executed to reduce delivery errors and ensure that entry-angle requirements were met. Figure 2 shows the requirement boundaries and the 99% post-separation entry-angle uncertainties as a function of OD data cutoff for the PTM-CU.

The OD delivery with a DCO on 22 December (Entry - 23 days), allowing PTM-CU execution on 23 December (Entry - 22 days), as listed in Table 1, met these requirements.

PTM was primarly a deterministic maneuver and, therefore, was placed so as to lower its ΔV magnitude. Although Fig. 3 shows the magnitude was a minimum near December 21, PTM was placed on December 17 to mitigate schedule risk.

With PTM on December 17, the OD uncertainty recovered to the converged level around December 19 [6, page 5-106] and made placement of PTM on or near December 17 relatively independent of PTM-CU placement (moving PTM earlier allowed OD to converge more quickly, giving better performance for PTM-CU) and, therefore, determined almost entirely by the trade between risk and ΔV.

The OD uncertainties, as one might expect, favored later dates for ODM-CU. In fact, to meet the relay-pointing requirement, the OD DCO for ODM-CU needed to be about Jan 3 or later [5, page 5-108]. Trading ΔV against risk, the DCO was placed one day before ODM-CU; ODM-CU was placed roughly Jan 4.

[2] This had to be balanced against the risk to performance introduced by placing OD DCOs earlier.

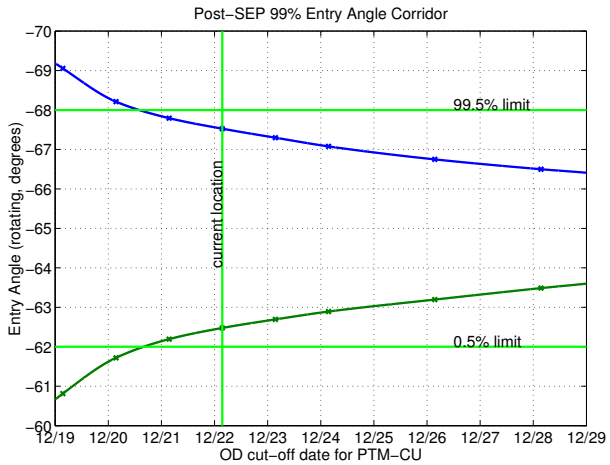

Figure 2. **Entry-Angle Corridor vs OD DCO.** *for varying dates of PTM-CU's OD DCO, the predicted entry-angle corridor is compared to the required corridor, both widths shown at 99%.*

On the other hand, both risk and ΔV were favorable to earlier execution dates for ODM. Figure 4 shows how the ΔV magnitude of ODM increases for later execution dates. However, proximity to another major event, SEP, was the limiting factor here, so ODM was placed about 3 days after SEP, as listed in Table 1. This time was needed for the OD estimate to converge before introducing more uncertainty to the estimate via ODM ΔV execution errors, for time to recover from potential problems after SEP, and to allow time for probe opnavs [11].

SEP had also been placed about as early as possible—about 2 days after PTM-CU. Those 2 days provided time to verify successful execution of PTM-CU and general readiness for probe separation.

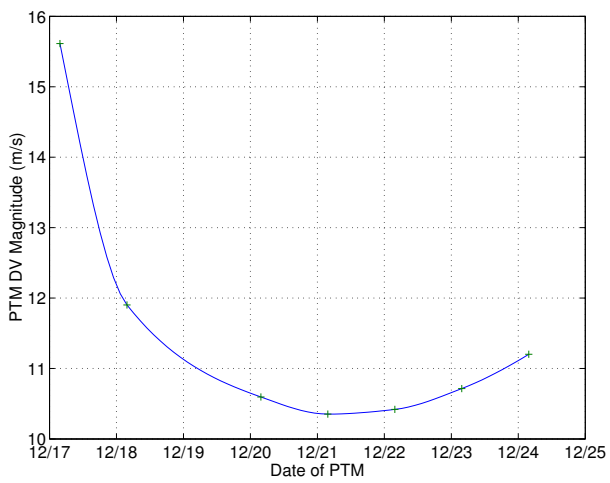

Figure 3. **PTM ΔV vs Date** *shows variation in the deterministic magnitude of PTM ΔV vs execution date.*

If SEP were delayed without redesigning PTM-CU, the probe-entry targets would take on some error. Of particular concern were the angle of attack and the entry angle. These variations were studied for up to 4 days of delay. The target parameters deviated fairly linearly from their nominal values, listed in Table 2. For each day of delay, the entry angle increased by 0.8° and the angle of attack increased by 0.03°. It was clear that even a delay of only one day in separation, without redesigning PTM-CU, would violate the required entry-angle corridor—the entry corridor did not have a margin large enough to accommodate the 0.8° shift that would be incurred for the delay of one day as neither end of navigation's predicted dispersion was more than 0.8° from -62° or -68°.

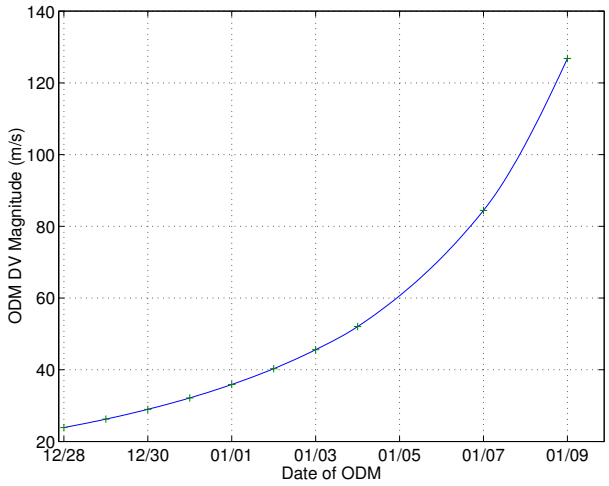

Figure 4. **ODM ΔV vs Date.** *shows variation in the deterministic magnitude of ODM ΔV vs execution date*

5. NAVIGATION ANALYSIS

A Monte Carlo simulation, using software called LAMBIC [12], is typically used at JPL to analyze a navigation strategy. A navigation strategy, at least, includes maneuver placement, maneuver-targeting strategy, maneuver execution error modeling [13], and OD estimation strategy. The latter two elements have not yet been discussed.

The maneuvers for the probe mission used the same execution error model, listed in Table 3, as any other maneuvers. This model was prepared prelaunch and partially updated with inflight data [14]. The model covered both types of maneuvers of the Cassini-Huygens spacecraft: Main Engine Assembly (MEA) (bipropellant) and RCS (monopropellant).

There are many elements to an OD strategy [11], but the only element listed here is the DCO for each maneuver. Table 4 shows the DCO used in actual operations for each maneuver. The OD DCOs used in the most recent analysis [6] are quite similar.

Table 3. **Execution Error Model (1-σ)** *Mag. is magnitude and Ptg. is pointing. Pointing model is per axis*

		MEA	RCS
Mag.	Proportional (%)	0.2	2.0
	Fixed (m/s)	0.01	0.0035
Ptg.	Proportional (mrad)	3.5	12
	Fixed (m/s)	0.0175	0.0035

Table 4. **OD DCO and Maneuver Delivery Statistics (1-σ)** *Delivery statistics are quoted for the Titan-c B-plane, quantities are computed at the nominal interface time for the probe and closest approach for the orbiter. The B-plane angle, θ, is referenced to Titan Equator of date. SMAA, SMIA in km.*

Mvr	DCO (UTC)	SMAA	SMIA	θ
PTM	15-Dec 16:08	640	10	179°
PTM-CU	21-Dec 14:10	34	6	4°
ODM	26-Dec 13:40	180	66	16°
ODMCU	2-Jan 17:16	22	6	89°

Results from the analysis [6] are summarized in Tables 5 and 4. In Table 5, "Det" or "deterministic" refers to the ΔV required in the reference trajectory, which is wholly deterministic, without any statistical contribution. The mean and $\Delta V95$ (95th percentile ΔV) listed account for both maneuver and OD statistical variations.

Table 4 lists delivery statistics for the maneuvers of the probe mission. These are computed in the inertial frame and Titan Equator of Date coordinate system. Delivery statistics indicate the 1-σ ellipse of the delivery covariance in the Titan-c B-plane if no maneuvers are executed after the one listed.

6. SOFTWARE TOOLS

The navigation team had anticipated the need to rapidly assess the current state of OD estimates in terms of an upcoming maneuver design and with respect to requirements. To serve that end, several special-purpose software tools were developed and certified [15]. The navigation team's responsibility ended at the interface altitude; any analysis that extended beyond that point was for the benefit of other teams.

Table 5. **Maneuver ΔV Statistics** *μ is mean ΔV, Des is the implemented design, and Err is the error as estimated by OD (err = estimate - design), all are in m/s. Data is taken from the Navigation Plan [5, 6].*

Maneuver	Det	μ	$\Delta V95$	Des	Err
PTM	11.9	11.9	12.1	11.9	-0.009
PTM-CU	0	0.14	0.3	0.0176	0.003
ODM	23.7	23.7	23.9	23.8	-0.008
ODM CU	0	0.20	0.36	0.14	0.004

The `probe_entry_tool` was used to predict, by generating and executing a small LAMBIC run, statistics for both the probe entry angle and angle of attack. Figure 5 shows a B-plane plot produced by this tool for the final PTM-CU design, showing that the predicted statistics would, in fact, meet the requirement.

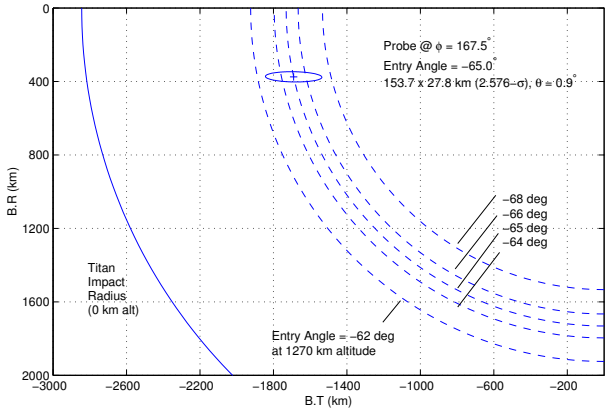

Figure 5. **Predicted post-PTM-CU B-plane Delivery.** *Ellipse shows 1-σ delivery contour. Includes contours for body-fixed entry-angle values to show that this delivery meets the entry-angle requirement.*

The `landing_predict` tool used data from a probe ephemeris file to make a rough landing-site prediction. The landing-site prediction was simply a projection onto Titan's surface of a point from the probe ephemeris near the interface altitude; with such simple modeling, it was an effective sanity-check against the more sophisticated approaches that included atmospheric modeling. The navigation team was not responsible for predicting the landing site, but was merely the most convenient team to perform this particular sanity check.

The `probe_relay_pointing_tool` was used to predict how well a given OD estimate and ODM-CU design could recover the nominal probe-relay pointing profile and what the uncertainty would be.

The `probe_relay_ivp_check` tool performed a comparison of the on-board relay-pointing profile to the best-estimate via ephemerides produced by the OD team. Plots from this tool were used to evaluate whether a candidate design for ODM-CU would meet the relay pointing requirements.

Each of these tools was used on a near-daily, if not daily, basis. For example, the entry-angle estimates were computed for each of the OD solutions made up to the Titan-c flyby. These entry-angle statistics are shown in Fig. 6, generated by the `probe_entry_tool`. The

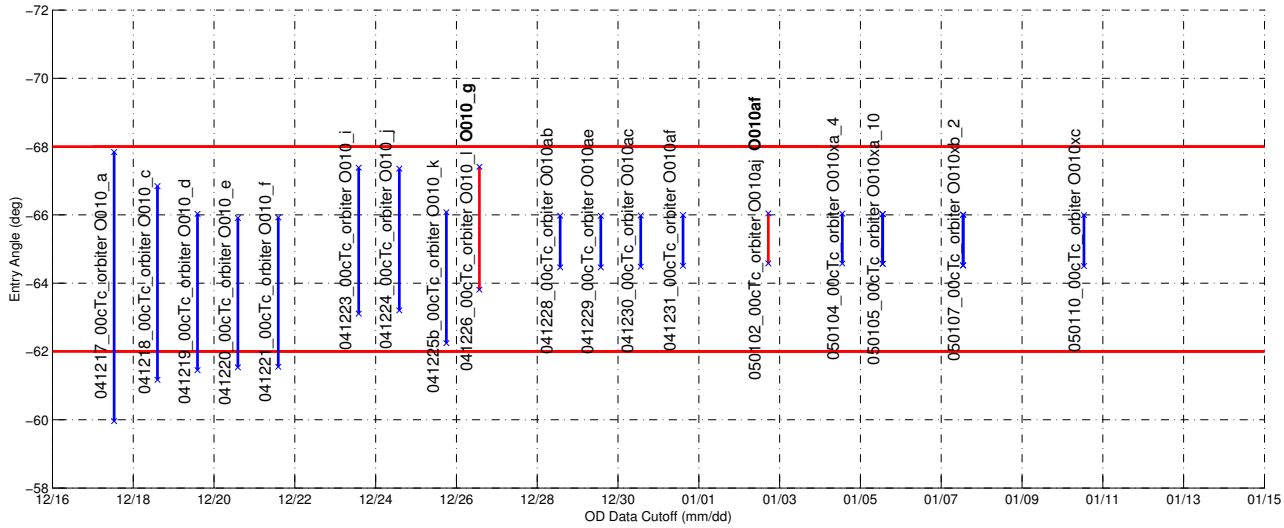

Figure 6. **History of Estimates for the Entry-Angle Corridor.** *Bars show extent of 99% level. Labels denote OD delivery and maneuver design names. Delivery after PTM-CU was 041223_00cTc and deliveries at ODM and ODM-CU were 041226_00cTc and 050102_00cTc. All predictions past the PTM-CU design on December 23 meet the requirement.*

plot shows that, prior to PTM-CU on December 23, the predicted corridor fell outside the requirement. Beginning with the PTM-CU design, every subsequent OD solution showed the corridor meeting the requirement. In fact, the OD solution apparently converged around December 28 and subsequent solutions for the corridor didn't show any noticeable change.

With these tools, the navigation team was able to bookkeep two parallel histories for PTM and PTM-CU designs. One history was the official targeting strategy where SEP was held fixed at the pre-probe-mission design. The second history included the option of redesigning SEP so that the angle-of-attack was target to 0°. By comparing the two designs, the navigation team gained additional confidence that the fixed-SEP strategy was sufficient.

7. RESULTS

In actual operation of the mission, maneuvers were executed according to the schedule in Table 1. OD was delivered according to the DCO epochs listed in Table 4. The maneuvers, as discussed, targeted the values listed in Table 2.

For comparison with the navigation analysis, the maneuver design ΔV magnitudes are listed alongside that data in Table 5. The analysis statistics held up quite well.

All indications during the mission were that maneuver execution errors were consistently small. After completing the mission, the OD team produced a detailed, best-estimate reconstruction of the trajectory, including maneuvers [11]; the maneuver team made a similar effort [16]. Table 2 includes data from that study, reduced to show just the observed error in each maneuver magnitude.

Based on the data in the reconstruction, all of the Huygens mission requirements were met by the navigation strategy described here, with a comfortable margin.

8. APPENDIX: B-PLANE DESCRIPTION

Planet or satellite targeting is described in aiming plane coordinates referred to as *B-plane* coordinates[17] (Fig. 7). The B-plane is a plane passing through the body center and perpendicular to the asymptote of the incoming trajectory (assuming 2 body conic motion). The "B-vector", $\mathbf{B}$, is a vector in that plane, from body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the body had no mass and did not deflect the flight path. Coordinates are defined along three orthogonal unit vectors, $\mathbf{S}$, $\mathbf{T}$, and $\mathbf{R}$ with the system origin at the body center. The $\mathbf{S}$ vector is parallel to the spacecraft V_∞ vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). $\mathbf{T}$ is parallel to a convenient reference plane, and $\mathbf{R}$ completes an orthogonal triad with $\mathbf{S}$ and $\mathbf{T}$. The reference plane for the $\mathbf{T}$ vector is generally the ecliptic plane (EMO2000). For Titan equator of date, the reference plane is in Titan's equatorial plane at the given epoch. With $\mathbf{S}$, $\mathbf{T}$, and $\mathbf{R}$ thus defined, a target point can be described in terms of the B-vector dotted into the $\mathbf{R}$ and $\mathbf{T}$ vectors ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$), or as the magnitude of $\mathbf{B}$ and the angle ϕ clockwise from $\mathbf{T}$ to $\mathbf{B}$.

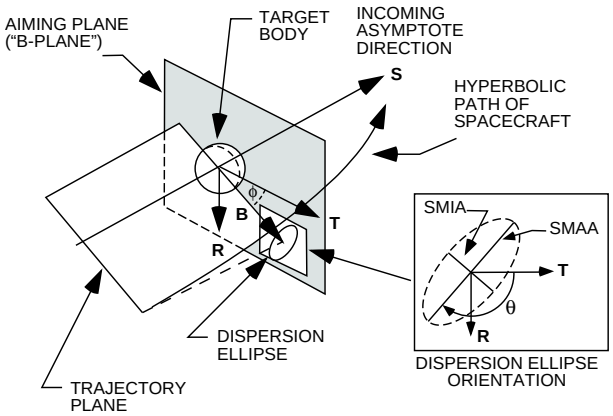

Figure 7. **B-Plane Coordinate System.**

Trajectory errors in the B-plane are often characterized by a one-σ dispersion ellipse, shown in Fig. 7. SMAA and SMIA denote the semi-major and semi-minor axes of the ellipse; θ is the angle measured clockwise from the $\mathbf{T}$ axis to SMAA. The dispersion normal to the B-plane is typically given as a one-σ time-of-flight error, where time-of-flight specifies what the time to swingby (periapsis) would be from some given epoch if the magnitude of the B-vector were zero. Alternatively, this dispersion is sometimes given as a one-σ distance error along the $\mathbf{S}$ direction, numerically equal to the time-of-flight error multiplied by the magnitude of the V_∞ vector.

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