APPROACH NAVIGATION FOR A TITAN AEROCAPTURE ORBITER

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Abstract

A proposed Titan aerocapture mission will send an orbiter and surface probe to Titan. Aerocapture technology will be employed to slow the spacecraft and perform the orbit insertion. The navigation strategy baselines ΔVLBI measurements and optical navigation imaging in order to satisfy the flight system performance requirements to the top of Titan's atmosphere. The performance requirement metric is the spacecraft's atmosphere entry flight path angle, which must fall within -36.8°±1.4 (3σ), although a tighter entry corridor is preferred if possible. The requirement can be satisfied with a data cutoff 12 days before Titan entry, assuming that an updated Titan ephemeris will be supplied by Cassini after completing its nominal mission at Saturn. There is margin in the arrival template to tighten (reduce) the entry corridor by scheduling a data cutoff closer to Titan. Improvements to the performance are discussed by anticipating enhancements to the current level of technological readiness. The probe can satisfy its entry flight path angle requirement of -50°±5 (3σ) by separating any time within 2 to 3 months of Titan.

Introduction

The Titan Orbiter (TO) mission will utilize solar electric propulsion during interplanetary cruise to deliver an orbiter and probe to Titan, and will employ aerocapture technology to assist with orbit insertion. The work presented here is part of a Titan mission study described in an overview paper given in Reference 1. That paper supplies details on other features of the mission.

The focus of this paper is a demonstration of the feasibility of direct-entry aerocapture as a replacement for an orbit insertion maneuver. The probe is considered secondarily only in so far as illustrating that probe requirements can be met.

This paper examines the navigation accuracies of the orbiter and probe as they approach and encounter Titan. Since there is a limit on the accuracy with which the initial state and subsequent dynamics are known, the future state cannot be computed with certainty from the initial one. The 'delivery' is defined as the uncertainty expected in the future spacecraft state (at its time-of-arrival*) computed at time T (where T is before the time-of-arrival). That is, a –2 day delivery represents the prediction (with dispersions) of the location of the spacecraft at arrival, when 2 days away from Titan.

The epoch for this analysis is Titan-75 days. There is no error analysis undertaken for the earlier part of the cruise.

Spacecraft Configuration

The design of the TO flight system is discussed in Reference 2. Externally, the flight system during Titan approach consists of two stacked aeroshells connected via an external truss. (The SEP propulsion module and associated solar array fans have been jettisoned earlier.) The TO spacecraft configuration is shown in Figure 1. The probe aeroshell is located on top and the orbiter aeroshell beneath. The probe and

* More specifically, 'entry time', defined on p. 4.

orbiter respectively are enclosed by the aeroshells, which consist of a backshell/ heatshield pairing. The aeroshell protects the contents from the high heat loads experienced during atmospheric entry.

An external truss connects the two aeroshells. Mounted on the truss is a rear-looking medium gain antenna (MGA) for telecommunications and navigation. Also mounted on the truss is (are) forward-looking camera(s) for optical navigation. The camera(s) should have independent pointing control.

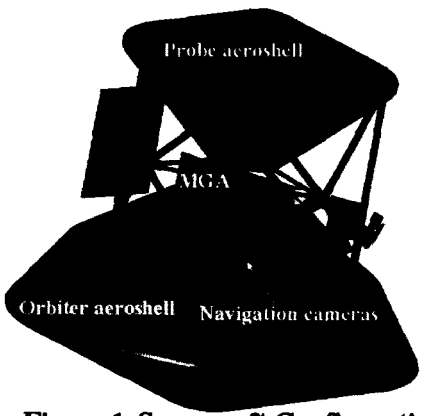

Figure 1. Spacecraft Configuration

The mass of the flight system (including propellant load) is 1465 kg. The orbiter represents 75% of the mass allocation and the probe/truss the remaining 25%.

Attitude Maintenance

For the navigation analysis, TO is assumed to be a 3-axis-fixed spacecraft with momentum-wheel ACS stabilization. The momentum wheels maintain spacecraft pointing. Balanced 0.7 N minimum impulse thrusters perform periodic, scheduled momentum de-saturation burns. (Note: momentum-wheel stabilization is not consistent with the baseline spacecraft design in Reference 2, which assumes limit-cycling ACS. The inconsistency has been identified but insufficient time was available to address this issue before the study ended.)

SEP Module

The SEP module consists of five Glenn Research Center 5 kW ion engines. Four engines operate at a time, leaving one engine in reserve. Each engine produces 0.15 N of thrust. Four solar array fans with a total area of 23 m^2 can generate 24 kWe at 1 a.u. [3]. The engines thrust while within the inner solar system, but when the solar range exceeds ~4 a.u. the SEP stage (including solar arrays) is discarded.

Propulsion

The propulsion system after the SEP is jettisoned is a monopropellant hydrazine system. This subsystem must perform spin control, attitude control, and trajectory correction maneuvers (TCMs) during the approach to Titan.

The thrusters are used for spin-rate control to spin-up the spacecraft before probe release. Subsequently the orbiter is spun-down and returned to 3-axis control.

Thrusters are used to de-saturate momentum wheels and to correct trajectory errors. All propulsive functions are performed with the RCS thrusters acting through ports in the backshell of the orbiter aeroshell (ports are not shown in Figure 1). After orbit insertion (without the aeroshell) the RCS thrusters perform the Titan pericenter raise maneuver.

Telecommunications

The telecommunications subsystem operates an X-band system for direct-to-Earth communications and a UHF system for communications with the probe during entry, descent and deployment (EDD).

A truss-mounted X-band medium-gain antenna (MGA) (with a low gain antenna back-up) is the only communication link during interplanetary flight. The MGA

design is a 24 dBi phase array antenna 28 cm in diameter. At 10 a.u.s from Earth the data rate to a 70 m ground antenna is 600 bps [2].

The probe backshell includes an aft-mounted LGA for UHF communications during EDD.

After orbit insertion (having discarded the MGA) a fixed 2.4 meter diameter high gain antenna located on the orbiter within the aeroshell will become operational.

Tracking and telemetry will use the Small Deep Space Transponder, which supports phase coherent two-way doppler and ranging, command signal demodulation and detection, telemetry coding and modulation, and differential one-way range (DOR) tone generation (tone sidebands at ±19 MHz). DOR tones are used for interferometric ΔDOR measurements.

Power

Multi-mission RTGs will power the orbiter. Two MMRTGs will produce a total of 4000 watts of heat, generating 252 watts (electric). Since the MMRTGs are stowed with the orbiter inside the aeroshell, heat pipes connect the MMRTGs to external radiators mounted on the truss.

Trajectory Design

The interplanetary reference trajectory characteristics are described in Reference 2. Since the reference trajectory has some fluidity during advanced study exercises (and changes frequently), the launch date chosen for this navigation investigation is December 15, 2010, and may not agree with the latest reference trajectory. The launch mass is 2515 kg, including the SEP module. The interplanetary trajectory includes a gravity assist flyby of Venus in May 2012 and arrives at Titan on August 21, 2016. The hyperbolic excess velocity at arrival is 6.1 km/s and the range to Earth is 9.8 a.u. (one-way light time equals 81 minutes).

The orbiter and probe initially approach Titan on an impact trajectory. After the probe separates from the orbiter bus it follows a ballistic path into Titan. The probe is nominally targeted to a mid-latitude region in the northern hemisphere (target TBD).

Before probe release the spacecraft is spun-up to a rate TBD (on the order of 3 rpm). After probe release the remaining orbiter bus and truss are spun-down and a trajectory deflection maneuver (TDM) is performed. See Figure 2, where on the scale of that figure the probe release and TDM appear to occur simultaneously. The truss is subsequently jettisoned before aerocapture.

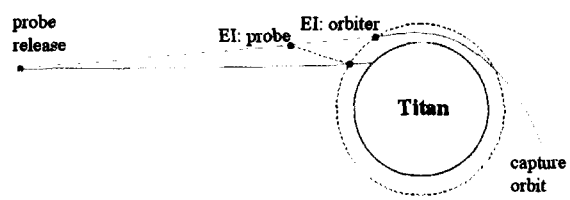

Figure 2: Entry Interface for Probe and Orbiter

The TDM serves two purposes: re-directing the orbiter's trajectory to intercept the orbiter entry interface point (a lateral movement of approximately 600 km in the B-plane), and slowing the orbiter with respect to the probe (a delay on the order of hours). This delay permits the orbiter to function as a communication relay for the probe during EDD.

Orbiter delay is a trade-off between probe transmitter power and the duration of EDD

and initial surface operations (to be relayed and recorded by the orbiter before aerocapture). In Figure 2 the blue line indicates the orbiter and the red line the entry probe. The position of the orbiter at the time of probe entry is indicated by the blue dot with the label "EI: probe" (Entry Interface for probe). For a delay of 3.5 hours, when the probe reaches its entry interface the distance between the probe and orbiter is approximately 80,000 km. The orbiter subsequently enters Titan's atmosphere at the blue dot labeled "EI: orbiter". By this time the probe has been transmitting data for about 3.5 hours.

The magnitude of the TDM as a function of probe release time and slow-down maneuver is parameterized in Figure 3. A probe release at E-30 days and TDM at E-29 days represents the baseline unless otherwise stated.

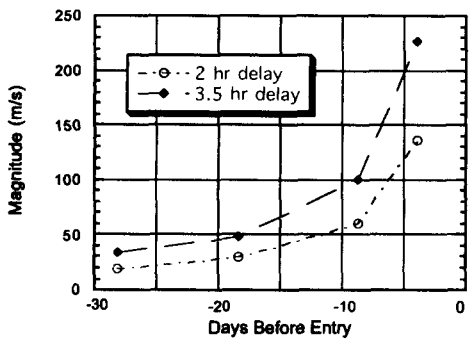

Figure 3: TDM magnitude v. probe release time

The encounter with Titan is a direct-entry arrival, phased to arrive at the satellite when Titan is receding from TO along the spacecraft's approach asymptote (*i.e.* at a point in Titan's orbit near the minimum TO-Titan relative velocity). The arrival at Titan is indeed direct – there is no Saturn orbit insertion occurring prior to TOI (*e.g.* as will happen with Cassini). The orbiter's closest approach to Saturn occurs 13 hours before Titan-arrival at a range of 1.2×10^6 km (approximately equal to Titan's orbital radius).

The trajectory during approach is pseudo-ballistic (the SEP module having been abandoned several years earlier) meaning that the spacecraft will depend upon traditional chemical thrusters for flight path control. The mission strategy targets Titan's north pole in order to place the spacecraft into a polar orbit.

Target Design

The entry interface target consists of three parameters: inertial entry flight path angle (FPA), B-plane angle, and entry interface radius, where the interface entry radius is defined to equal 3575.0 km *i.e.* an altitude of 1000 km. The flight path angle is the angle subtended by the vehicle trajectory with the local horizontal at the EI, and it defines a corridor through the atmosphere (see Figure 4). The corridor's width is constrained by upper and lower bounds determined by the physical limitations of the flight system (vehicle must be able to withstand aerodynamic, structural, and heat loads), and by the need to accumulate sufficient drag forces to slow the spacecraft (to avoid skip-out).

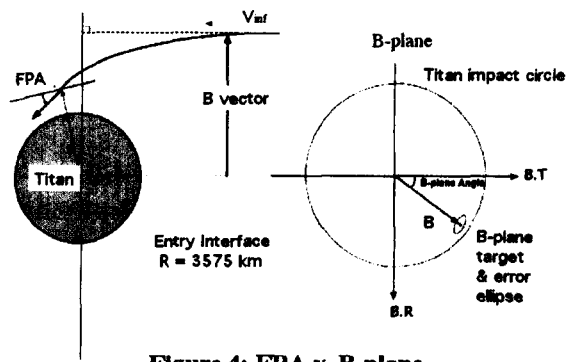

Figure 4: FPA v. B-plane

For the orbiter, the entry interface target is derived from the characteristics of the vehicle aerodynamics and the post-insertion Titan orbit. For the probe, the entry

interface target is derived from the desired landing site (latitude and longitude).

The orbiter flight system at Titan is designed for an inertial entry velocity of 6.5 km/s and an entry FPA of -36.8°±1.4 (3σ) [4]. The probe is designed to satisfy an entry FPA of -50°±5 (3σ) [4]. The atmosphere at Titan (mostly nitrogen and methane) has a surface density of 5 kg/m^3 (5x Earth), corresponding to a surface pressure of ~1.5 bar [5]. Subject to these conditions, an FPA of -50° will subject the probe to a maximum deceleration of 10 g's. For the orbiter an FPA of -36.8° will subject the orbiter to a maximum deceleration of 4 g's (assuming the baseline atmospheric density profile described in Reference 6).

The orbiter descends to an altitude of ~300 km before exiting the atmosphere (also a function of atmosphere density) [6]. Two hours after aerocapture a propulsive maneuver will raise pericenter out of the atmosphere and circularize the orbit. For an entry velocity of 6.5 m/s the pericenter-raise Δv will equal 230 m/s. The entry interface target and orbit characteristics (after circularization) are provided in Table 1.

Table 1: Orbiter Entry Interface Target and Post-insertion Orbit Characteristics

Entry time: Aug 20, 2016 23:56:18 UTC

EI Target				Orbit Characteristics		
Altitude (km)	Latitude (deg)	eFPA (deg)	Entry Velocity (km/s)	Altitude (km)	Inclination (deg)	Period (hours)
1000	80N	-36.8	6.5	1700	100	5

Navigation Data

Optical Data

Navigation optical data will consist of digital images of Titan, other Saturnian satellites, and possibly Saturn, set in front of a stellar background. Background stars, combined with planetary ephemerides, establish the spacecraft-Titan relative position by astrometry. And since radiometric data are unable to resolve a gravity signature from Titan until a spacecraft is nearly upon it, target imaging is important for approach navigation.

The optical navigation campaign begins at E-75 days. (In practice, it's more likely that navigation images would start as early as T-180 days.) Ground-based facilities will process transmitted pictures to extract the optical observables; then the data will be combined with radiometric measurements.

Opnav transmissions will be constrained by the downlink data rate (600 bps). Probably more significant, however, are conflicts with competing spacecraft activities. Anticipating such demands during the last fortnight of cruise, a maximum rate of one opnav per every 2-4 hours was selected as a reasonable compromise [7].

At the beginning of the approach phase, one picture every other day is shuttered. (Titan's orbital period is 16 days.) The picture frequency increases to five per day, and increases again to approximately ten opnavs per day within 16 days of Titan. This yields approximately 200 images in the optical data set.

The imaging system envisioned here follows a design similar to the Mars Reconnaissance Orbiter optical navigation camera. Relevant technical specifications of the advanced (MRO) camera are: aperture = 6 cm, focal length = 50 cm, field-of-view = 1.4° per side, detector = 1024x1024 CCD array, pixel resolution = 50 μrad, mass = 2.7 kg, peak power = 4 W [8]. For comparison, the Cassini navigation camera has these specifications: aperture = 6 cm, focal length = 20 cm, field-of-view = 3.5° per side, detector = 1024x1024 CCD array, pixel resolution = 60 μrad, mass = 27 kg, peak

power = 35 W [7]. The advanced (MRO) camera offers higher resolution yet weighs less and is more energy efficient.

See Appendix 1 for optical data weights.

Tracking Data

The baseline navigation data set throughout the mission consists of two-way coherent X-band doppler and two-way coherent X-band range measurements. These data are augmented during approach with optical observations and ΔVLBI measurements.

Table 2: Doppler and Range Tracking Coverage

Start	End	Coverage
E-75days	E-41	3 tracks/week
E-40	E-11	2 tracks/day
E-10	Entry	3 tracks/day

ΔVLBI data enhances the navigation solution relative to that achievable with doppler, range and optical data (although it is the optical data that dominates in a ranking of the relative importance of the four data types). In general ΔVLBI data, or specifically for this analysis Delta Differenced One-way Range (ΔDOR), has limited effectiveness because of the spacecraft's distant location in the solar system, but it can be used to great advantage in combination with other data types.

Data frequencies used in this analysis for doppler, range and ΔDOR are provided in Tables 2 and 3. Data weights are provided in Appendix 1.

Table 3: DDOR Coverage

Start	End	Observation Frequency
E-75days	E-51	1 per week
E-50	E-35	3.5 per week
E-34	Entry	14 per week

Navigation Performance

Significant error sources in the navigation model are listed below. (Also see Appendix 1which lists all error sources and *a priori* uncertainties.) Each error source is either estimated in the filter or considered. The combined effect of maneuver execution errors and orbit determination errors mapped to the atmospheric entry interface point is called the delivery accuracy.

Ephemeris Determination

Bounds on the Titan ephemeris errors in the year 2016 are given in Table 4. The tabulation is given in a Saturn-centered RTN coordinate system, where R represents the radial direction, T the down-track direction and N the out-of-plane direction.

Table 4: Titan, Saturn and Earth Ephemeris Uncertainties (3σ)
Mapped to August 21, 2016

Central Body	R (km)	DT (km)	OOP (km)	RSS
Earth	0.01	2.6	3.9	4.7
Saturn GB*	95	405	135	437
Saturn BOC	27	81	51	99
Titan GB*	120	570	300	655
Titan BOC	6	482	6	492**
Titan EOC	1	30	1	104**

* Representative of accuracies currently possible from ground-based observations. Not mapped to 2016.
** Combined with Saturn BOC error.

Significant improvements to the Titan ephemeris between now and 2016 should occur. The suffixes BOC and EOC in Table 4 illustrate this improvement with respect to current ground-based observational knowledge (indicated by "GB"). "BOC" (beginning of Cassini) denotes Titan's ephemeris knowledge shortly before Cassini's arrival at Saturn. "EOC" (end of Cassini) represents the expected Titan ephemeris knowledge in 2008 after approximately 44 Cassini flyby encounters. The improvement is appreciable.

The BOC and EOC ephemeris accuracies in Table 4 include secular degradation to 2016.

Maneuver Determination

Maneuvers scheduled during the approach phase are listed below. Table 5 defines the baseline targeting strategy adopted for this analysis (last targeting maneuver at E-24 hours), while Table 6 illustrates an alternative targeting strategy (last targeting maneuver at E-6 hours). The important difference between the two strategies, however, is the probe release time. For the strategy outlined in Table 5, the probe is released at E-30 days whereas the alternative strategy releases the probe at E-5 days. (A late release time, *i.e.* E-5 days, is preferred in order to reduce probe instability growth after separation and achieve an accurate delivery.)

Table 5: PR-30 Approach Phase TCMs

TCM*	Time**	OD Data Cutoff**	Description
TCM-1	E -60 days	E - 65 days	Correct SEP cruise errors; penultimate probe targeting.
TCM-2	E -31 days	E - 33 days	Final probe targeting to probe-entry aim point.
PR	E -30 days	E – 30 days	Probe release.
TCM-3 (TDM)	E -29 days	~E – 30 days	Deflect orbiter to entry interface point.
TCM-4	E – 9 days	E – 11 days	Correct deflection maneuver errors; penultimate targeting.
TCM-5	E – 24 hrs	E – 48 hrs	Final orbiter targeting to orbiter-entry aim point.

*Numbered starting at the beginning of the approach phase.
**With respect to orbiter entry (E) time.

TDM (TCM3) is a deterministic maneuver, and its parameterized magnitude as a function of probe release time is plotted in Figure 3. The remaining maneuvers in Tables 5 and 6 are all small statistical maneuvers in comparison to TDM. The magnitudes of these clean-up maneuvers have not been analyzed, but the mean Δv for TCM1 and TCM2 probably will not exceed 1 m/s each for either strategy. For the PR-30 strategy, the combined total of TCM4 and TCM5 will be on the order of 5-10 m/s (at a confidence level of 1σ). For the PR-5 strategy, the mean Δv for TCM4 and TCM5 will be much greater.

The 1σ execution errors assumed here are: fixed magnitude error of 1 mm/s, proportional magnitude error of 1% per axis, fixed pointing error of 1 mm/s per axis, and proportional pointing error of 2 milliradians per axis for the deflection maneuver and 1 milliradians per axis for the other TCMs.

Table 6: PR-5 Approach Phase TCMs

TCM	Time	OD Data Cutoff	Description
TCM-1	E –60 days	E - 65 days	Correct SEP cruise errors; penultimate probe targeting.
TCM-2	E -6 days	E - 8 days	Final probe targeting to probe-entry aim point.
PR	E -5 days	E – 5 days	Probe release.
TCM-3 (TDM)	E -4 days	~E – 5 days	Deflect orbiter to entry interface point.
TCM-4	E -24 hrs	E – 48 hrs	Correct deflection maneuver errors; orbiter targeting.
TCM-5	E -6 hrs	E – 15 hrs	Final orbiter targeting to orbiter-entry point.

Orbit Determination

The dominant orbit determination uncertainties consist of the reaction caused by the probe release mechanism, ephemeris errors, TCM execution uncertainties, and data errors. All TCMs within the data arc are estimated, plus a single future TCM (*i.e.* the TCM immediately following the data cutoff time).

Results

Delivery errors are a combination of orbit determination errors and maneuver execution errors. Results for both the orbiter

bus and entry probe are presented here. Unless noted otherwise, all results assume EOC Titan ephemeris knowledge. Sensitivities examined were: delivery improvements due to optical navigation data and/or ΔDOR observations, and entry FPA uncertainties parameterized by probe release time and/or the orbiter over-flight delay.

Orbiter Vehicle. Mission OD uncertainties in the Titan B-plane for a probe release time of E-30 days and an over-flight delay of 3.5 hours are shown in Figure 5. TDM is not shown in Figure 5; it lies off the left edge of the figure. But it's the rapid reconstruction of TDM (*i.e.* falling FPA uncertainty shown in Figure 5) that enables aerocapture to be undertaken.

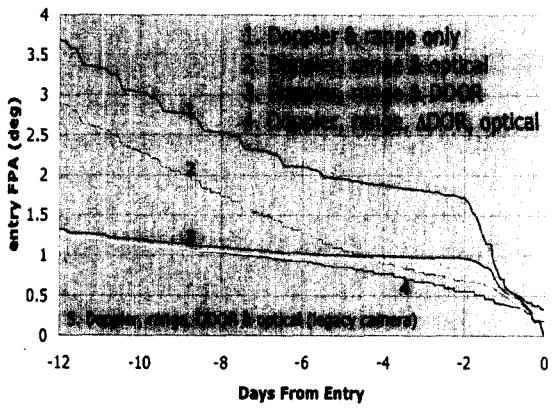

Figure 5: FPA v. Time-to-Go (3σ)

Sensitivities are shown in Tables 7 - 10. Table 7 illustrates the improvement in the overall delivery accuracy due to the incremental addition of advanced data types to the basic doppler and range data set. The results in Table 8 show the delivery sensitivity to probe release time. Table 9 shows the effect of varying the *a priori* Titan ephemeris. Table 10 lists the probe delivery accuracy.

Margin remains in the navigation sub-system. Table 7 (and Figure 5) show that the delivery requirement can be satisfied by any of the tracking options. (Including the doppler and range-only option, if the E-30 hours delivery is selected.)

Table 7: Orbiter Delivery Accuracy (3σ) Data Sensitivity

Probe release = E-30 days, Over-flight delay = 3.5 hours	Doppler & Range Only	Doppler Range & ΔDOR	Doppler Range & Optical	Doppler Range Optical ΔDOR
Preliminary Reqm't	±1.4	±1.4	±1.4	±1.4
Nominal Delivery				
Data Cutoff at E-48 hours				
Semi-major axis (km)	68.7	39.1	28.1	23.3
Semi-minor axis (km)	17.4	16.0	13.3	11.7
Ellipse angle (deg)	75.2	66.0	64.9	53.7
Entry time (s)	17.5	9.1	6.7	4.8
B magnitude (km)	68.7	38.6	27.6	22.0
Flight Path Angle (deg)	±1.7	±1.0	±0.7	±0.6
Alternate Delivery				
Data Cutoff at E-30 hours				
Semi-major axis (km)	37.0	30.0	21.9	20.9
Semi-minor axis (km)	16.1	14.2	12.6	10.9
Ellipse angle (deg)	65.3	55.0	57.4	48.0
Entry time (s)	10.9	7.9	5.5	4.0
B magnitude (km)	36.5	28.5	21.1	19.2
Flight Path Angle (deg)	±0.9	±0.7	±0.5	±0.5
Parameter Update				
Data Cutoff at E-3 hours				
Semi-major axis (km)	15.8	7.2	13.1	7.1
Semi-minor axis (km)	1.5	1.6	1.5	1.7
Ellipse angle (deg)	56.2	57.2	56.3	57.9
Entry time (s)	3.4	1.3	1.5	1.2
B magnitude (km)	14.9	6.9	12.3	6.7
Flight Path Angle (deg)	±0.4	±0.2	±0.3	±0.2

The magnitude of TDM is expected to be proportional to the probe release time and to the telecommunication capabilities of the probe. Greater orbiter eFPA uncertainties will be expected for large distances between the orbiter and probe (*i.e.* long delay times) and for late probe release times (*i.e.* closer to Titan). This performance is illustrated in Table 8.

Knowledge of Titan's orbital position increases during Cassini's tour (Table 4). This improvement is apparent in the TO flight path angle errors shown in Table 9.

Table 8: Orbiter Delivery
Probe Release Time v. Over-flight Delay
Entry FPA Uncertainty (3σ)

	Probe Release E – 30 days		Probe Release E – 5 days	
Over-flight Delay ->	3.5 hrs	2 hrs	2 hrs	1 hr
E – 48 hours (deg)	±0.6	±0.6	±1.1	±1.0
E – 30 hours (deg)	±0.5	±0.4	±0.9	±0.8
E – 3 hours (deg)	±0.2	±0.2	±0.6	±0.6

Table 9: Orbiter Delivery
Probe Release Time v. Ephemeris Sensitivity
Entry FPA Uncertainty (3σ)

Probe Release = E - 30 days, Over-flight Delay = 3.5 hours		
Titan ephemeris ->	circa 2008 (EOC)	circa 2004 (BOC)
E – 48 hours (deg)	±0.6	±0.7
E – 30 hours (deg)	±0.5	±0.6
E – 3 hours (deg)	±0.2	±0.3

The delivery dispersions of entry interface states resulting from monte carlo simulations of navigation errors are shown in Figure 6. The larger scatter (grey points) represents the B-plane uncertainty at the E-2 day delivery, while the tighter scatter (black points) depicts the uncertainty at an E-3 hour delivery.

The E-2 day scatter shown in Figure 6 maps into flight path angle uncertainty shown in Figure 7. Figure 7 plots FPA as a function of entry velocity for the E-2 day delivery. The scatter is not clustered around -36.8° because the navigation entry states are mapped to 1 minute before EI (radius = 3821 km) and not the EI (radius = 3575 km).

Earlier Study. A navigation analysis undertaken in May 2002 generated preliminary results for the Titan aerocapture study group, as discussed in Reference 1. The results presented here represent more recent analyses. (In the earlier study, although the advanced camera was also investigated, it did not represent the baseline case. Ephemeris revisions have also occurred since then.).

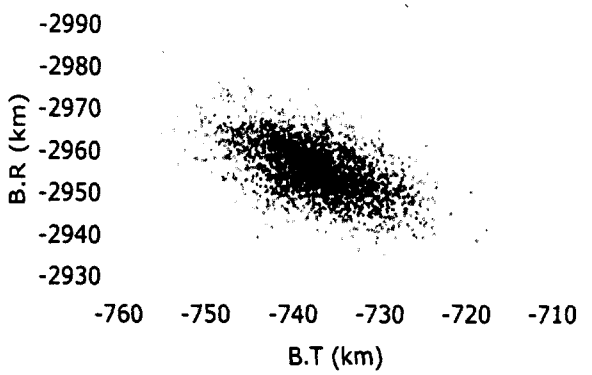

Figure 6: E-2 day and E-3 hour Deliveries Mapped to Entry Interface Point*

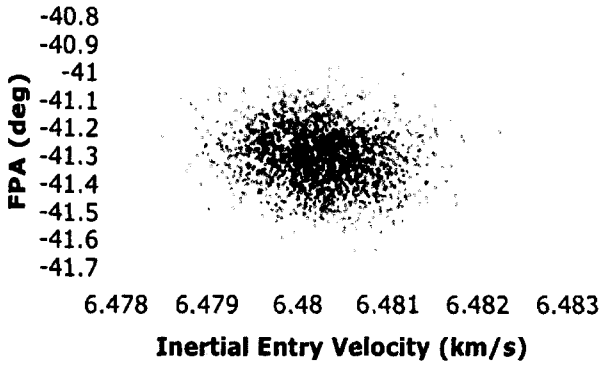

Figure 7: FPA v. Entry Velocity at EI*

Probe capsule. The last probe targeting maneuver occurs thirty-one days before entry (in the baseline case). Subsequent to that maneuver the spacecraft spins up to prepare for probe release. At E-30 days the probe separates from the spacecraft bus. Contact with the probe is broken for 30 days while the probe falls ballistically towards Titan. Upon reaching the entry interface point (radius equal to 3575 km) the probe begins broadcasting telemetry on UHF. The orbiter, at that time about 80,000 km behind the probe, begins relaying the probe's data to Earth for the next 3.5 hours. (If the probe is an aerobot, the probe aeroshell will spend about 90 minutes

* 99% confidence level; mapped to 1minute before entry.

sinking through the atmosphere before deploying the aerobot.) Contact with the probe is lost at about the time the orbiter reaches its entry interface point.

The requirement to deliver the probe to Titan can be satisfied, as shown in Table 10, for either an E-30 day release or an E-5 day release. The latter probe release time delivers the probe to Titan with higher accuracy. Indeed, the probe can separate as early as ~E-90 days and still meet the delivery requirement with the assumptions used here.

Table 10: Probe Delivery Accuracy (3σ) Probe Release Time and Camera Sensitivity

	Probe Release E – 30 days		Probe Release E – 5 days	
Camera Design	circa 2008	legacy camera	circa 2008	legacy camera
Preliminary Requirement	±5.0	±5.0	±5.0	±5.0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The probe model differs in minor ways from the bus model. The significant differences to note for the probe are the uncertainties with its initial state due to the probe-release mechanism, the absence of any trajectory correction maneuvers after separation, and the paucity of tracking data after separation.

Discussion

Significant navigation benefits accrue by assuming Titan's position will be known to about the same level of certainty when TO arrives as will exist at the time of Cassini's last flyby of Titan. This is a reasonable assumption since Titan's orbit has few perturbations and over a decade any error growth should be small (unlike the Galilean satellites of Jupiter). The sensitivity of the TO delivery to Titan's ephemeris is shown in Table 9.

Optical navigation images of Titan, because of its atmosphere, have relatively large uncertainties associated with them, especially in the week before entry. This uncertainty can be partially mitigated by incorporating navigation pictures of the small, icy moons of Saturn, but an atmosphere degrades the optical data in a way that an airless satellite would not.

Optical navigation nevertheless is an important component in the navigation data suite, although its relative utility diminishes given precise and accurate Titan position knowledge. The EOC Titan uncertainty in Table 4 is nearly equal to the accuracy achievable with optical navigation from TO (within a factor of ~2). Therefore opnavs contribute proportionally less to navigation early in the approach phase because errors other than Titan's ephemeris dominate (*e.g.* error in the spacecraft state). See plot 2 in Figure 5. In addition to a measurable improvement to the TO delivery from incorporating the Cassini EOC-level Titan ephemeris, modest improvements in camera technology can also improve the TO delivery (the difference between plots 4 and 5 in Figure 5).

ΔDOR improves delivery accuracy when incorporated (see Figure 5 and Table 7). This improvement in delivery accuracy comes about because the *a priori* Titan ephemeris represents position uncertainties less than the corresponding data noise in the opnav camera (early in the approach phase). So delivery knowledge is not dominated by ephemeris errors, but rather by the spacecraft's state uncertainty. ΔDOR observations decrease spacecraft errors and therefore improve the delivery. Only when the spacecraft approaches within four days of Titan does optical data dominate the solution.

ΔDORs and optical data are orthogonally complementary and thus can combine to

yield plot 4 in Figure 5. This is the best delivery in the current study. Note that plot 5 represents a similar simulation, but with a less advanced camera. In the latter case optical data noise swamps ephemeris and spacecraft errors, resulting in less precise orbit determination.

There is no advantage to using K-band tracking in place of X-band. There may be benefit to K-band ΔDOR observations, but this parameterization has not yet been explored.

Separation of the TO probe from the orbiter can occur as early as approximately 90 days before Titan and satisfy the probe's entry requirements. However, at the opposite end, for a separation equal to E-5 days, several disadvantages become apparent. The maneuver schedule in the last week is compressed significantly with respect to a separation at E-30 days or earlier. The magnitude of the deflection maneuver (TDM) is large. The advantage, however, is an accurate probe delivery to Titan.

The data arc used for the E-30 day probe release consists of 30 optical navigation images and 32 ΔDOR observations. With this data set the requirement to deliver the probe to Titan is satisfied, as shown in Table 10. For the E-30 day release time, both the baseline case (circa 2008 camera) and a less capable legacy imaging system provide equivalent probe deliveries, and well within the requirement.

Entry time uncertainty for the probe is 20 seconds (3σ) for the baseline case (*i.e.* for an E-30 day release, four navigation data types, EOC ephemeris). The relay link on the orbiter bus needs this much margin in the telecom design.

The Titan Orbiter mission is boosted by SEP during cruise, but during the approach phase and in orbit conventional thrusters control the spacecraft. As a rough estimate of propellant loading, for an E-30 day separation and a 3.5 hour over-flight delay, the spacecraft will need to carry propellant sufficient to perform about 300 m/s of velocity change, including both deterministic and statistical maneuvers (up to and including the post-insertion orbit circularization burn, but not including on-orbit maintenance propellant).

Entry FPA results or expected results from other missions are summarized in the table below. (MER and Huygens have not yet arrived at Mars and Titan respectively at the time of this writing.)

Table 11: Delivery Accuracy Comparison (3σ) TO Orbiter and Probe v. Other Missions

Mission	Entry FPA	Error	Delivery Time	Reqm't
TO orbiter	-36.8°	±0.6°	E-2 d	±1.4
MPL	-12.0°	±1.0°	E-2 d	~±0.5
MER	-11.5°	±0.2°	E-2 d	±0.25
TO probe	-50.0°	±1.9°	E-30 d	±5.0
Galileo probe	-8.6°	±0.6°	E-140 d	±1.4
Huygens probe	-64.0°	±3.0°	E-21 d	±3.4

MPL and Huygens stand out in the short list above with high uncertainties.

The MPL mission was characterized by unbalanced and mis-modeled thrusting activities. The level of thrusting required by the ACS system to maintain attitude significantly exceeded pre-launch expectations, and this mis-modeling contributed to the entry flight path angle uncertainty shown in Table 11.

Huygens will be released from Cassini 21 days before entry and, with an uncertainty of +/-3.0°, is not significantly different from

the TO probe delivery. The Huygens delivery is larger than the TO probe partly because it does not have access to the Titan EOC ephemeris. Another reason is the tour re-design Cassini has undergone recently [9]. The release time is no longer as favorable for probe delivery, subjecting Huygens to additional perturbations.

The MER delivery, on the other hand, is significantly smaller than MPL and the TO delivery. This is attributable to well known Mars' ephemerides, a larger gravity-well, and lack of a TDM (and no force mis-modeling).

Summary

This study has baselined the use of optical observations and ΔDOR measurements in addition to doppler and range data for delivering a probe and orbiter to Titan, and has assumed a Cassini-era Titan ephemeris. The orbiter can satisfy its preliminary entry FPA requirement of ±1.4° (3σ) as early as 12 days from Titan. At E-2 days that delivery improves by 250% (*i.e.* to ±0.6°). The E-2 day delivery is sensitive to ΔDOR measurements, and the delivery accuracy is shown to improve by 0.1° vis-à-vis only doppler, range and optical data, which is a significant improvement. An alternate delivery at E-30 hours reduces the baseline E-2 day FPA uncertainty by an additional 15%.

Initial results indicate that the orbiter cannot meet preliminary entry requirements using a pre-Cassini ground-based *a priori* Titan ephemeris such as that described in Table 4.

This work represents a first-cut effort at determining concept feasibility. Many simplifying assumptions were made, especially with respect to the optical data, in order to accomplish this study in a timely manner. Further detailed analyses should be performed.

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Appendix 1: *A Priori* Navigation Model Uncertainties

Error Source	*A Priori* Uncertainty (1σ)	Correlation Time	Comments
Data			
doppler (mm/s)	0.1	–	X-band or Ka-band
range (m)	20	–	relatively high uncertainty in lieu of range biases
ΔDOR (nrad)	4	–	0.11 ns (X-band)
optical (pixels)	0.25 - ~5.0	–	larger error corresponds to smaller range
Estimated Parameters			
epoch state			
position (km)	1000	–	
velocity (km/s)	1	–	
Saturn ephemeris (km)	(9, 27, 17)	–	R,AT,OOP, circa 2016 (5% DE405 error)
Saturn mass (km^3/s^2)	0.0002	–	circa 2016 (from simulated ephemeris)
Saturn pole direction (mdeg)	(0.12, 0.14)	–	R.A., Dec, circa 2016 (from simulated ephemeris)
Titan ephemeris (km)	(1, 10, 1)	–	R, AT, OOP, circa 2016 (from simulated ephemeris)
camera pointing error (deg)	(0.5, 0.5, 2)	0	R.A., Dec, Twist; estimated per observation
non-gravitational accelerations (km/s^2)	1.0×10^{-12}	10 days	spherical covariance, estimated daily (1 day batches)
solar pressure (%)	10	–	reflectivity coefficient
ACS ΔV (mm/s), 1 every 3 wks	(2, 2, 2)	–	(line-of-sight, lateral, normal) components
TCMs (mm/s)			spherical covariance
TCM-1	4	–	3% (3σ) proportional error (per axis) 3 mm/s (3σ) fixed error (per axis)
TCM-2	2	–	
probe release	5	–	probe release at E - 30 days
TCM-3	330	–	TCM3 at E - 29 days
TCM-4	5	–	TCM4 at E - 9 days
TCM-5	7	–	TCM5 at E - 1 day
Earth pole direction (cm)	2 → 10	0	(X and Y). Ramps to higher value during final week of data. (For UT1, ~10 cm -> 0.26 ms.)
UT1 (cm)	2 → 10	0	
ionosphere - day (cm)	55	0	S-band values
ionosphere - night (cm)	15	0	
troposphere (cm)	1	0	
Considered Parameters			
station locations (cm)	3	–	
quasar locations (nrad)	2	–	for ΔDOR data

Appendix 2: *B*-plane Description

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "*B*–plane" coordinates (see Figure). The B-plane is a plane passing through the body center and perpendicular to the asymptote of the incoming trajectory (assuming two body conic motion). The "B-vector" is a vector in that plane, from the body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target body had no mass and did not deflect the flight path. Coordinates are defined by three orthogonal unit vectors, **S**, **T**, and **R**, with the system origin at the center of the target body. **S** is parallel to the spacecraft v_∞ vector (approximately the velocity vector at the time of entry into the target body's gravitational sphere of influence). **T** is arbitrary, but typically specified to lie in the ecliptic plane (the mean plane of the Earth's orbit), or in the body equatorial plane. Finally, **R** completes an orthogonal triad with **S** and **T**.

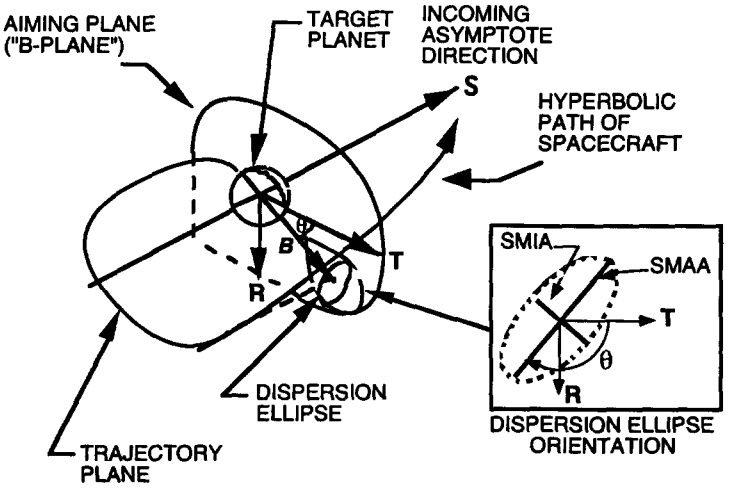

Fig. Aiming Plane Coordinate System Definition

Orbit determination errors can be characterized by a statistical dispersion ellipse in the aiming plane (*B*–plane) and a statistical uncertainty along the **S** (down-track) direction. In the Figure, SMIA and SMAA denote the semi–minor and semi–major axes of the dispersion ellipse (*i.e.* 50% of the distance across the ellipse along the respective coordinate). The angle θ is measured clockwise from **T** to SMAA.