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MISSION DESIGN FOR THE TITAN SATURN SYSTEM MISSION CONCEPT

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In 2008, NASA and ESA commissioned a study of an international flagship-class mission to Titan, Saturn, and Enceladus consisting of a NASA orbiter and two ESA *in situ* elements, a montgolfière hot air balloon and a lake lander. This paper provides an overview of the trajectory design for this mission, which consists of a solar electric interplanetary trajectory to Saturn, a gravity-assist tour of Titan and Enceladus, delivery of the two *in situ* elements, Titan aerobraking, and a Titan circular orbit.

INTRODUCTION

In 2008, following from NASA's 2007 Outer Planet Flagship Mission studies and ESA's 2007 Cosmic Vision proposals (TandEM and Laplace), NASA and ESA commissioned joint studies of both a Titan Saturn System Mission (TSSM)[1-2] and a Europa Jupiter System Mission (EJSM)[3-4] . As a result of those studies and independent review, NASA and ESA prioritized EJSM for launch in 2020 (consisting of a NASA Europa orbiter and an ESA Ganymede orbiter) with TSSM to follow.

Per the study ground rules for the joint 2008 NASA-ESA study, TSSM was directed to investigate Titan as its primary target but to also include Enceladus and the Saturn System as Level 1 requirements. The ground rules also specified that NASA would provide the orbiter and ESA would provide in situ elements. Figure 1 shows the complete TSSM flight system concept that includes a NASA-provided orbiter/SEP stage and two ESA-provided in situ elements (montgolfière hot air balloon and lake lander). The purpose of the paper is to describe the robust mission design that responds to the ground rules and achieves all stated objectives.

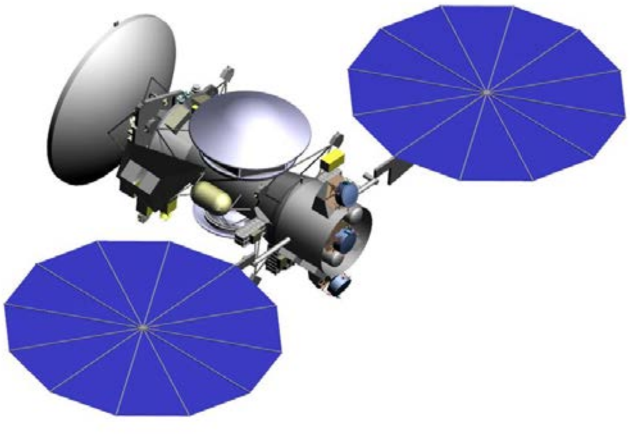

Figure 1. *TSSM Flight System*

(conceptual design)

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Table 1. *Mission phase definition and description*

Phase	Activity	Duration
Interplanetary Cruise (9 years)	Launch and Early Operations: Launch from CCAFS and activities, including initial acquisition by the DSN, checkout and deployment of all critical spacecraft systems and preparations to begin thrusting with the Ion Propulsion System (IPS).	2 months
	Solar-Electric Cruise: Thrusting with the IPS and gravity-assist flybys of Earth and Venus. Several activities associated with flybys, thrust arc design, and Earth avoidance.	5.0 years
	Ballistic Cruise: Once the SEP stage is jettisoned, the spacecraft enters a period of low activity.	3.3 years
	Saturn Approach: Preparations and readiness testing for Saturn Orbit Insertion (SOI). Optical navigation for upcoming Enceladus flybys.	6 months
Saturn Tour (2 years)	Saturn Arrival: SOI performed between Cassini-like ring plane crossing in the F–G gap	2 years
	ISE Delivery: Starts with 214 d period orbit with a Balloon Targeting Maneuver (BTM) to target to the montgolfière entry position and velocity, release of the montgolfière, and a Periapsis Raise Maneuver (PRM) to target the first Titan flyby. On the following orbit, a Lander Targeting Maneuver (LTM), Lander Release, and Orbiter Deflection Maneuver (ODM) deliver the Lander to Kraken Mare.	
	Enceladus Flybys: Seven close (100–500 km) flybys of Enceladus allowing *in situ* measurements of the plume and remote sensing of active region. Additional opportunistic flybys of other icy moons possible, such as Rhea in the example tour.	
	Final Energy Reduction: Series of orbits with large maneuvers to lower Titan V_∞ to ~940 m/s prior to Titan orbit insertion. Moderate-sized maneuver sets up proper initial orbit plane geometry.	
Titan Orbit (1.9 year)	Aerobraking: Starting from an 720 km by 15,000 km orbit, Titan aerobraking is used to help circularize orbit and provide deep sampling of Titan atmosphere to 600 km.	2 months
	Circular Orbit: Detailed surface mapping of Titan from a 1500 km, circular, polar (85°) orbit that starts with and a decending node at 11:30 am LST and reaches 9:00 am by the end of the mission.	20 months
Decommissioning and Disposal	At end of prime mission, a ~15 m/s maneuver places spacecraft in an orbit that will decay in < 6 months. During this phase small maneuvers will be used to keep the final entry point away from any regions of concern for planetary protection.	6 months
Extended Mission	Minimal orbit maintenance requirements mean that the spacecraft could continue in Titan orbit for an extended mission of several years as allowed by funding and spacecraft health.	

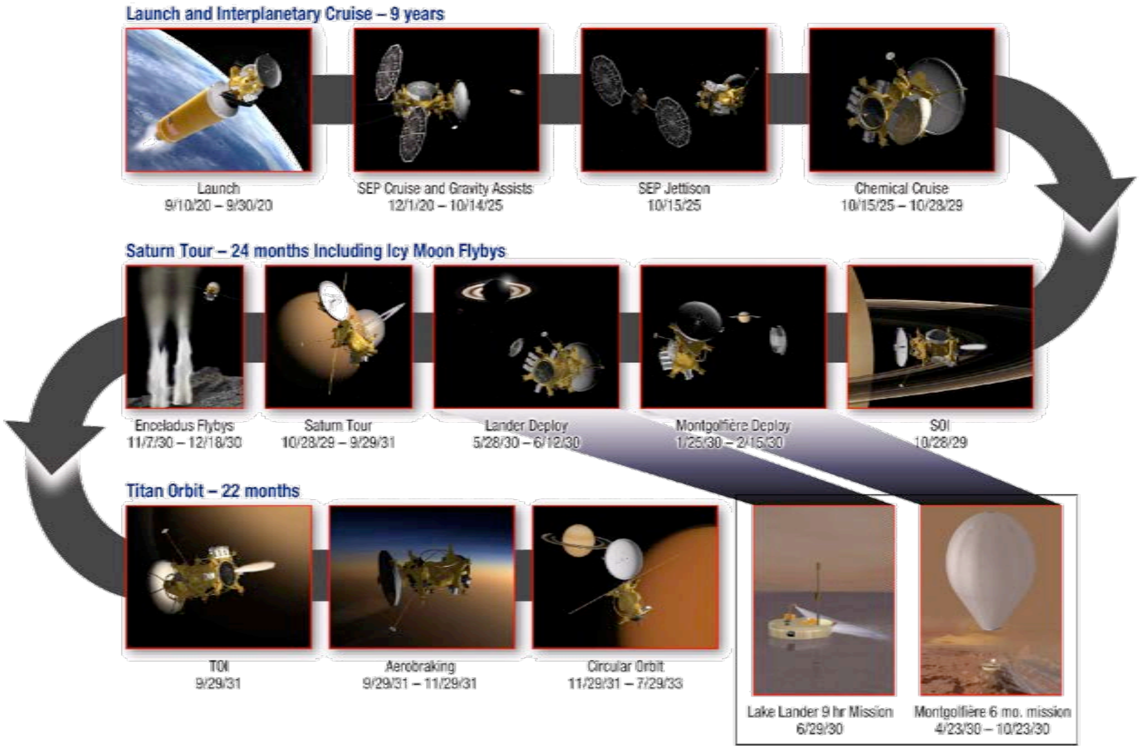

Figure 2. *TSSM mission timeline*

This paper will focus primarily on the mission design for the NASA orbiter. Both NASA and ESA have publically available reports[1-4] that give details on science objectives and flight system design for the NASA and ESA flight elements, as well as the mission design for the ESA in situ elements.

Figure 2 is a graphical timeline showing the various phases of the TSSM mission that will be discussed in the following sections. Table 1 gives the mission phase names with a description of the activities that take place in each phase.

TSSM MISSION DESIGN

Overview

For the TSSM baseline design, the NASA orbiter with both of the ESA provided in situ elements would be launched together in September 2020 on an Atlas V 551 from Cape Canaveral. The flight system would then perform a nine-year interplanetary trajectory with solar electric propulsion in combination with gravity-assists of Venus and Earth to reach Saturn in October 2029.

After a 746 m/s Saturn Orbit Insertion (SOI), the orbiter would begin a two-year Saturn Tour Phase with 16 Titan and 7 Enceladus flybys. An ESA-provided RPS-powered montgolfière would be delivered on the first Titan flyby, and an ESA-provided battery-powered lander would be delivered on the second Titan flyby.

After the two-year Saturn tour, the orbiter would enter Titan orbit with a 388 m/s Titan Orbit Insertion (TOI) maneuver on September 29, 2031. The 22-month Titan Orbit Phase would begin with a 2-month Aerobraking Phase. Over these 2 months, the apoapsis altitude would be reduced from 15,000 km to 1500 km via Titan aerobraking passes. The orbit would then be circularized to a 1500 km, near-polar (85°) mapping orbit. This orbit begins with a descending node at a Local Solar Time (LST) of 11:30 am, which progresses to 9:00 am by the end of the 20-month Circular Orbit Phase.

At the end of the mission, a small de-orbit burn would place the spacecraft on an orbit that would decay and impact Titan by the end of the 6-month Decommissioning and Disposal Phase. This decaying orbit would be controlled and the final impact point of the spacecraft can be deflected away from regions several hundred kilometers across. This would enable the mission to avoid any regions of planetary protection concern where the possibility of near-surface water may have been identified during the mission.

Table 2. *21-day launch period for 2020 opportunity.*

	Beginning of Launch Period	Middle of Launch Period	End of Launch Period
Date	Sep 10	Sep 19	Sep 30
C_3 (km^2/s^2)	0.60	0.64	0.64
DLA (deg)	-19.5°	-20.5°	-21.2°
Launch Mass (kg)	6265	6265	6265
SEP ΔV (km/s)	2.63	2.68	2.77
Xenon Fuel (kg)	390	397	410

Table 3. *Interplanetary events.*

Event	Date / Altitude
Launch	Sep 10–30, 2020
Start SEP Thrusting	Dec 1, 2020
Earth-1	Oct 27, 2021 / 16,900 km
Venus	Feb 4, 2022 / 5300 km
Earth-2	Jun 11, 2023 / 4500 km
Earth-3	Jun 11, 2025 / 600 km
End SEP Thrusting	Oct 14, 2025
SOI	Oct 28, 2029

Launch

The spacecraft would begin its journey on an Atlas V 551 rocket launched from Cape Canaveral. Table 2 details the prime launch opportunity in 2020 (the backup opportunities are detailed in a later section). Because TSSM uses Solar Electric Propulsion (SEP) to reach Saturn, there is virtually no change in performance over the

21-day launch period required by the study ground-rules. The launch C_3 doesn't change enough to get different launch masses from the KSC ELV performance website,[5] hence the identical launch masses. Moreover, the use of SEP would enable the launch period to be extended well beyond the 21 days shown for no additional mass penalty.

Interplanetary Trajectory

Figure 2 shows the SEP trajectory used to reach Saturn. Table 3 details the flybys and other major events during the interplanetary cruise from launch to Saturn arrival. The SEP thrusting and gravity-assist flybys occur during the solar electric cruise, which lasts for 5 years after launch. At the end of the SEP thrusting, the SEP stage will be released such that it will impact Saturn (in order to alleviate planetary protection concerns). Following the SEP thrusting, the next 3.3 years is a ballistic cruise with no flybys. Six months prior to Saturn arrival, activity increases to prepare for SOI and to begin taking optical navigation images to support the tour's Enceladus flybys.

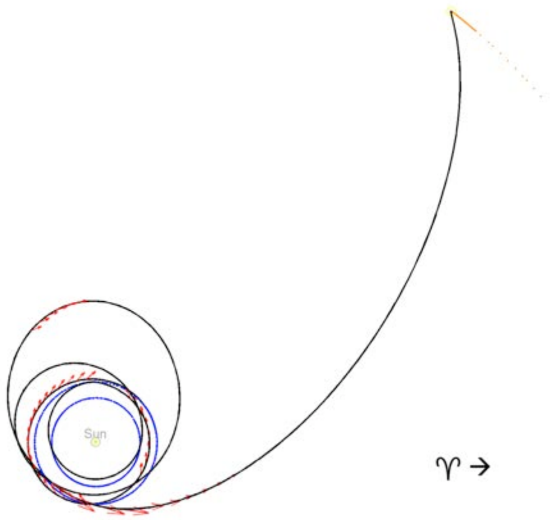

Figure 2. *2020 EVEE SEP trajectory with arrows showing thrust periods and directions.*

Table 4. *SEP trajectory constraints.*

Parameter	Value	Rationale
Flight-System Power Margin	5%	Arrays are sized to provide 15kW after accounting for a 5% margin on total system power
Trajectory Power Margin	5%	Reduced power protects against heliocentric range variations across operational contingencies
Propellant Margin	10%	Provides robustness to engine performance changes
Planned Thrust Outages	3%	Period of planned thrust arcs lost to downtime for spacecraft maintenance tasks, solar conjunction, etc.
Unplanned Thrust Outages	5%	Robustness to unplanned thrust outages
Forced Coast after Launch	60 d	Two months for initial checkout of spacecraft and Ion Propulsion System (IPS)
Coast during Flybys	+/- 1 d	Coast period to avoid any problems with solar eclipse and for thermal control during Venus flyby
Minimum Flyby Altitude	400 km	Assumes a minimum operational Earth flyby altitude of 300 km (based on Galileo studies) with 33% margin for robustness to missed thrust.

Table 4 lists the design assumptions used for the low-thrust trajectory design. These assumptions are intended to give margin to the design and allow for future design refinements such as robustness to periods of missed thrust and implementation of targeting strategies for the Earth flybys. The values in this table result from a study conducted at JPL of appropriate margins for SEP missions.[6] A principal difference in Table 4 from the recommendations of the JPL SEP margins study is shorter forced coast periods around flybys and the use of 3% for planned thrust outages as opposed to the 5% recommended by the study. This is because TSSM does not have planned thrust outages for radiometric tracking or long tracking periods around flybys. This is possible because the flight system design can accommodate radiometric tracking during thrust periods as a result of the articulating high gain antenna and accelerometers (10 nano-g) sensitive to <1% of the ion thrust magnitude.

The SEP trajectory allows sending more mass to Saturn than chemical trajectories. This is principally due to the addition of a 1-year Earth-to-Earth leg after launch that substantially reduces the launch C_3 needed from 11–19 km^2/s^2 for chemical in the 2018–2022 launch years to only 0.6–1.4 km^2/s^2.

For the types of SEP trajectories examined in the past, the mass of the SEP stage (778 kg, including margin) offset much or all of this mass advantage. However, this study has developed and applied powerful new methods for finding SEP trajectories that make use of inner solar system gravity assists to provide superior performance.[7]

This design currently uses three high performance NEXT ion engines (up to two thrusting with one as a spare) and UltraFlex solar arrays that provide 15 kW of power at 1 AU. The TSSM report[1] details alternate trajectory options using other electric propulsion systems as well as chemical propulsion trajectory options.

Saturn Tour Trajectory

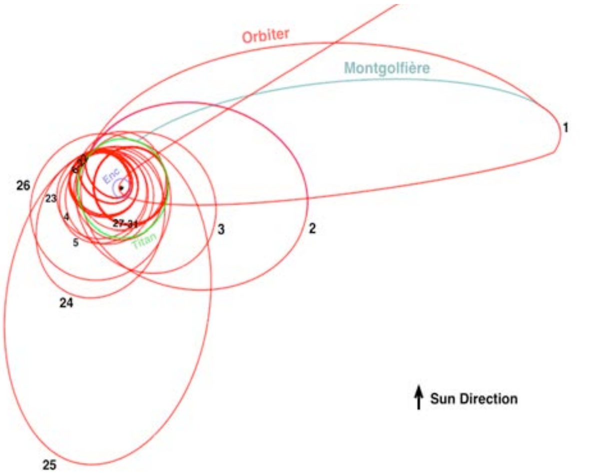

Figure 3. *Planned Saturn Tour Phase showing orbits numbered from SOI to TOI.*

This phase begins with Saturn Orbit Insertion (SOI). On either side of SOI, the spacecraft crosses through the same gap between the F and G rings used by Cassini. During these crossings, like Cassini, the High Gain Antenna (HGA) would be put in the ram direction and used as a dust shield. Cassini has given us a much better understanding of the debris environment near the rings and TSSM could pass closer to the F-ring than Cassini did. This saves propellant and gives opportunities for spectacular observations of the rings. In addition, Cassini's observations of the D-ring have opened up an exciting possibility of a passage between the D-ring and Saturn that would be examined during Phase A for possible additional ΔV savings. The entire SOI burn would be visible to Earth and can be monitored via the spacecraft's low gain antenna (LGA).

The 2-year gravity-assist tour is required to deliver the montgolfière and lander, provide flybys of Enceladus with *in situ* sampling of its plume, and to reduce the orbiter energy prior to TOI for efficient capture at Titan. This tour is designed to the constraints given in Table 5. The minimum flyby altitude given in this table is a function of flyby v-infinity due to atmospheric heating. For the Aerobraking Phase, the spacecraft is designed to tolerate atmospheric heating of up to 0.25 W/cm^2. Table 6 gives the flyby altitudes where that heating is achieved using the atmospheric models developed for the TSSM study.[1] The minimum altitudes in Table 5 are above these values to give additional margin for navigation performance.

A two-year tour is detailed in Table 7 and depicted in Figure 3. This tour is part of a fully integrated, end-to-end trajectory from launch to spacecraft disposal used to confirm the feasibility of the TSSM mission design and to generate an accurate ΔV budget. It is point-design representative of a much larger space of possible tours. After a decision to start the TSSM project, starting in Phase A and continuing through Phase E, a tour design effort would be undertaken to optimize the TSSM tour for Science to the level of the Cassini extended mission design. It is reasonable to expect that such an effort will lead to significant improvement over what is already an exciting tour design.

Table 5. *Tour design constraints*

Parameter	Value	Description
Duration	2 yr	Duration balances Saturn tour science with Titan orbit science.
Enceladus Flybys	4+	Must achieve at least 4 close flybys over Enceladus South pole.
Minimum Titan Altitude for Vinf < 3 km/s	800 km	Accounts for spacecraft heating limits with margin for navigational accuracy. First low Titan flyby is limited to 900 km to confirm atmospheric model.
Minimum Titan Alttitue for Vinf < 2 km/s	750 km	Accounts for spacecraft heating limits with margin for navigational accuracy.
Minimum Titan Altitude for Vinf < 1 km/s	720 km	Accounts for spacecraft heating limits with margin for navigational accuracy.
Minimum Enceladus Flyby Altitude	100 km	Leaves margin for navigational uncertainty. This may likely be lowered to 50 km or even 25 km after more detailed analysis.
Minimum time between low altitude flybys	8 d	Close flybys must be separated by at least 8 days to allow sufficient time for maneuvers. Distant flybys may be closer if targeted as a Cassini-style double flyby.
Solar Conjunction	Avoid Conjunction	Tour maneuvers and flybys placed with consideration of Ka-band limits of > 3° SEP for commanding and telemetry, and > 7° SEP for radiometric tracking.

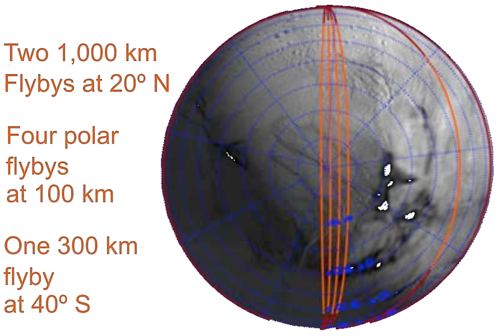

Figure 4. *Enceladus Flybys*

Table 6. *Titan flyby heating limits*

Flyby V-Infinity	0.25 W/cm^2 Heating Altitude
3 km/s	720 km
2 km/s	680 km
1 km/s	650 km

Table 7. *Saturn tour design showing flyby altitude and v-infinity along with post-flyby Saturn orbit inclination and period*

	Body	Date	Alt [km]	Vinf [km/s]	Per [d]	Inc [deg]
SOI	Saturn	28-Oct-29	11236	6.6	214.0	5.7
Ti1	Titan	26-Apr-30	1000	2.8	91.3	17.2
Ti2	Titan	29-Jun-30	1200	2.7	45.6	24.1
Ti3	Titan	31-Jul-30	900	2.7	22.9	26.6
Ti4	Titan	16-Aug-30	1077	2.7	22.9	19.3
Ti5	Titan	1-Sep-30	800	2.7	22.8	5.3
Ti6	Titan	17-Sep-30	2331	2.7	15.1	0.6
Rh1	Rhea	5-Oct-30	1273	3.6	15.5	0.5
Ti7	Titan	18-Oct-30	1817	2.8	11.4	0.5
Ti8	Titan	3-Nov-30	1241	2.8	10.0	0.5
En1	Enceladus	7-Nov-30	1000	7.1	9.8	0.5
En2	Enceladus	14-Nov-30	100	7.1	9.8	0.5
En3	Enceladus	21-Nov-30	100	7.2	9.8	0.5
En4	Enceladus	28-Nov-30	307	7.1	9.8	0.5
En5	Enceladus	5-Dec-30	100	7.1	9.8	0.5
En6	Enceladus	11-Dec-30	100	7.1	9.8	0.5
En7	Enceladus	18-Dec-30	1110	7.2	9.8	0.5
Ti9	Titan	21-Dec-30	2128	2.8	11.4	4.8
Ti10	Titan	6-Jan-31	2687	2.8	15.2	4.8
Ti11	Titan	7-Feb-31	3460	2.8	22.9	3.8
Ti12	Titan	23-Feb-31	2717	2.8	45.7	1.5
Ti13	Titan	27-Mar-31	3477	2.8	133.9	0.5
Ti14	Titan	29-Jun-31	750	1.7	43.4	0.3
Ti15	Titan	28-Jul-31	720	0.96	22.9	5.1
Ti16	Titan	13-Aug-31	2570	0.95	17.2	7.9
TOI	Titan	29-Sep-31	760	0.94		

Table 8. *Distant flybys <100,000 km.*

Date	Moon	Altitude [km]	Vinf [km/s]
28-Oct-29	Enceladus	23,000	17.5
31-Oct-30	Tethys	46,000	6.6
14-Nov-30	Mimas	86,000	11.3
14-Nov-30	Tethys	87,000	6.1
4-Dec-30	Tethys	73,000	5.7
26-Dec-30	Enceladus	32,000	2.8
4-Jan-31	Rhea	55,000	5.2

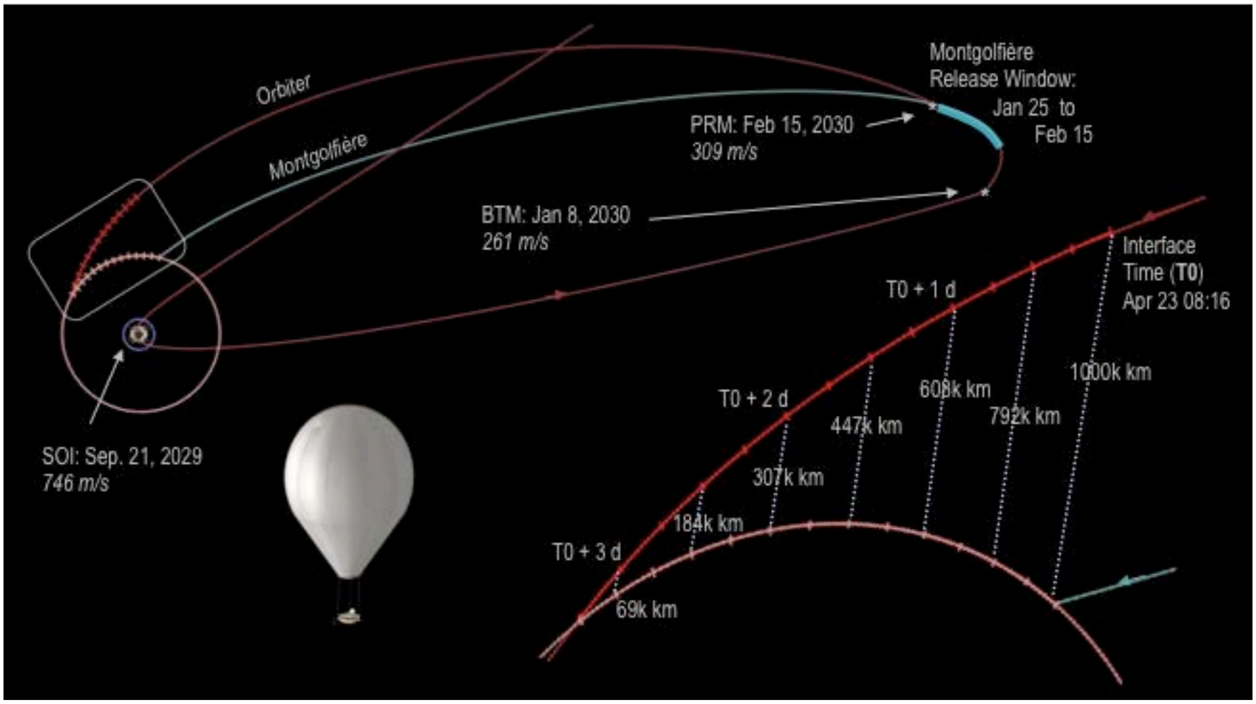

Figure 5. Montgolfière Delivery

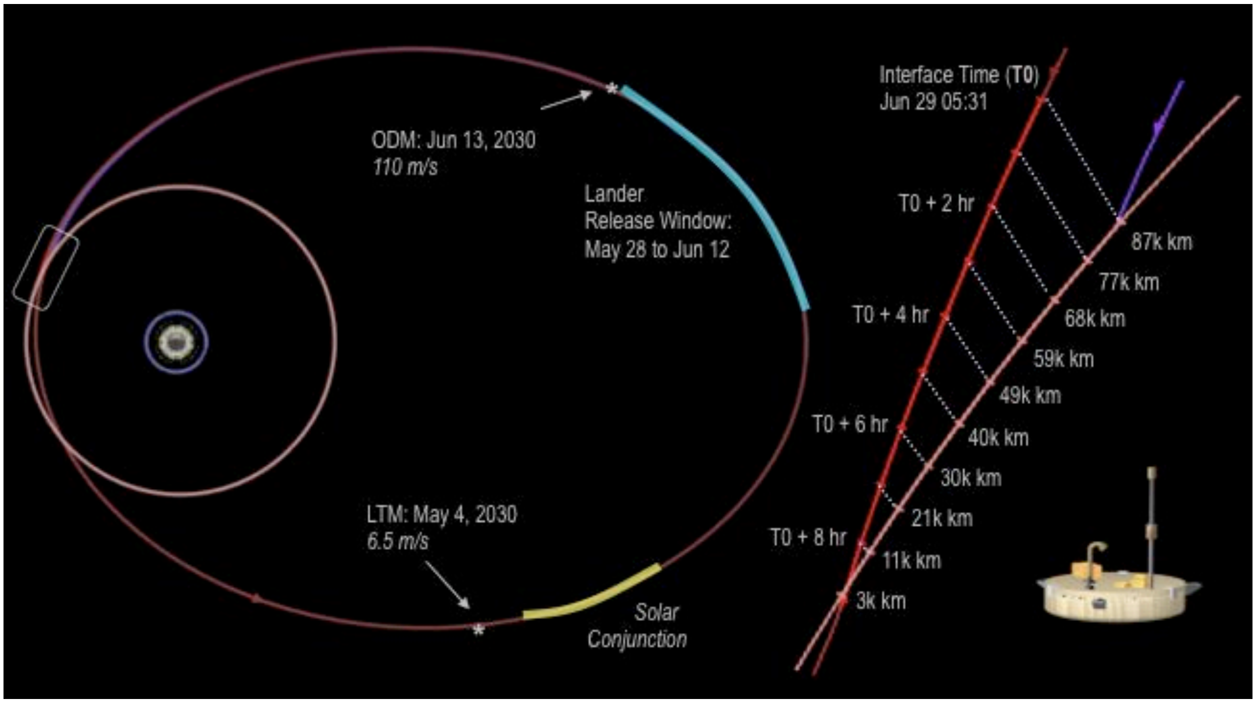

Figure 6. Lander Delivery

A primary focus of the Saturn tour design is the Enceladus flybys, which are optimized to make best use of TSSM instrumentation that is greatly enhanced relative to that carried by Cassini. These flybys currently target the active region at the Enceladus south pole (see Figure 4). However, it is possible to retarget these encounters in-flight if the active region changes at the time of the TSSM mission. Such a change in activity could be determined from distant observation of Enceladus prior to the close flyby phase.

Although Enceladus is a key driver of the tour design, the rich cadre of icy moons at Saturn will provide many fortuitous opportunities for science. In addition to the close Rhea flyby shown in Table 7, there are several other distant flybys of the icy moons shown in Table 8. These flybys provide many targets of opportunity that add to the TSSM tour science beyond the focus on Titan and Enceladus used for the tour design.

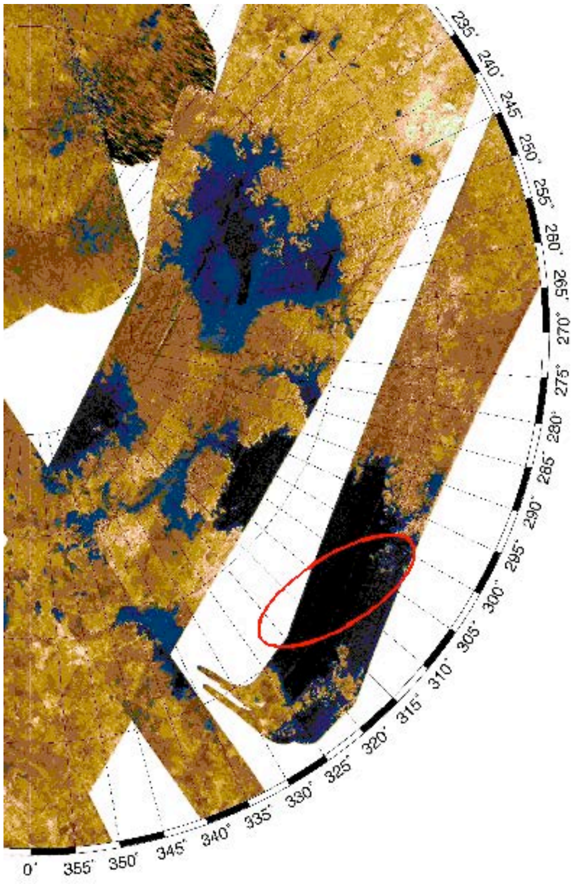

Figure 7. *Kraken Mare landing site.*

Delivery of *In Situ* Elements

Two *in situ* elements[2] provided by ESA are carried on the orbiter and released at the beginning of the tour. After SOI, a Balloon Targeting Maneuver (BTM) targets the montgolfière to 20°N, where winds are thought to be strong enough at the montgolfière's 10 km altitude to maximize the likelihood of at least one circumnavigation of Titan. After BTM, there is a three-week period from January 16, 2030 to February 6 during which the montgolfière can be released. Following release, on February 7, the orbiter performs a Periapsis Raise Maneuver (PRM) to lower its Titan V-infinity to 2.8 km/s for the upcoming Enceladus flybys. On the next orbit, the lander is released (also with a 21-day window) prior to the second Titan flyby and targeted to Kraken Mare, a hydrocarbon sea in Titan's arctic region. Figures 5 and 6 detail the timeline for release and arrival of the *in situ* elements.

Table 9. *In situ element entry parameters.*

Parameter	Value
Montgolfière Destination	20° N at steady state
Montgolfière Interface Altitude	2000 km
Montgolfière Entry Speed	6.3 km/s
Montgolfière Entry Ang. Corridor	65° +/- 3° (3-sigma)
Mont. Release Vel. Uncertainty	35 mm/s (1-sigma)
Lander Landing Site	72°N 310°W, Kraken Mare
Lander 3-σ Landing Footprint	600 km E-W X 160 km N-S
Lander Interface Altitude	2000 km
Lander Entry Speed	3 km/s
Lander Entry Angle Corridor	65° +/- 1.5° (3-sigma)
Lander Release Vel. Uncertainty	35 mm/s 1-sigma

The montgolfière would arrive at Titan in daylight, in the morning, and has ~6 Earth days until Titan nightfall. For the lander, its landing site in Kraken Mare is above Titan's arctic circle and does not get sunlight at the time of the mission due to Northern winter. Therefore, the lander is designed with a lamp for illumination of its immediate vicinity (to look for possible material floating on the surface of Kracken Mare) and does not require daylight. Kraken Mare would be a vast featureless expanse of open Sea at the landing site and little information is expected to be gained from imaging beyond the immediate vicinity. When the lander arrives, the Sun is ~22° below the horizon, but a gibbous Saturn is visible and provides 2.5 times the light of a full moon at Earth. An alternate delivery of the Lander is also possible which would arrive in twilight when the Sun is only ~8° below the horizon and Saturn is in a crescent phase providing roughly the illumination of one full moon.

The delivery of both elements is operationally robust in offering three-week windows for the releases. Should this robustness not be sufficient, contingency tours could be developed (as were developed for Cassini-Huygens) that would enable either element to be delivered on a subsequent Titan flyby. Such contingencies would insert an additional orbit in the tour and shift the orbiter's TOI 6–8 months later for a montgolfière contingency and 2–4 months later for a lander contingency. Such contingencies could be developed during the project's operational phase when the tour design is finalized if the project determines that the three-week windows in the current design are not sufficiently robust.

Table 9 details the delivery targets for the *in situ* elements along with the delivery dispersions. This table also gives the landing ellipse. Figure 7 shows the landing ellipse for the lander on a polar plot of Kraken Mare.

A covariance study was done for another case with release of the montgolfière and lander several months prior to SOI (an earlier iteration of the TSSM design). This study found that the principal sources of error at the 2000 km interface were: 1) time from release to entry, 2) errors introduced by the separation mechanism, and 3) radiation pressure from any RPS on the *in situ* element. Moreover, it was found that this error at the interface altitude was a small factor in determining the size of the landing ellipse compared to errors introduced by winds during descent. A good approximation of the relative effects of these two error sources is that the delivery errors at the interface lead to the smaller North-South axis of the landing ellipse, and that wind induced errors lead to the larger East-West axis. To decrease the North-South axis would require reducing delivery errors (e.g., by reducing the time from release to entry) and to decrease the East-West axis would require reducing the effect of the winds (e.g., by reducing the descent time with a smaller parachute).

The constraints in Table 9 arose from this study, which showed that velocity uncertainties on the order of 20–25 mm/s on the *in situ* elements after release were achievable with a Cassini-Huygens like delivery scheme. The entry angle constraints and delivery dispersions at the interface reflected in Table 9 are possible with velocity uncertainties of ~35 mm/s at release.

In Situ **Element Relay**

The montgolfière would be a long-lived vehicle with a radioisotope power source. During its nominal six month mission the primary relay for the montgolfière is through the TSSM orbiter, although limited direct to Earth (DTE) communication is also possible. The relay will occur during some Titan flybys and while the orbiter is in Saturn orbit. This would allow a total data transfer of >1.3 Tb.

The lander would be a short-lived battery powered probe with a nominal three-hour surface mission and a six-hour descent. Its only relay would be to the TSSM orbiter, which will provide a dedicated nine-hour relay period during the second Titan flyby with a capability of 3.4 Gb of data.

The critical events of entry, descent, and landing (EDL) for the lander and the entry, descent, and inflation (EDI) for the montgolfière would be visible for radio monitoring via relay with the orbiter. The montgolfière's EDI could also be monitored from Earth, but that is not required. Figures 5 and 6 depict the relay geometry for both elements during these periods.

The relay from the orbiter to both elements is X-band through the High Gain Antenna (HGA). When the orbiter is > ~500,000 km in range the HGA beam width is sufficient to cover the entire visible hemisphere of Titan. However, when the range is sufficiently close, the footprint from the HGA is smaller than the *a priori* knowledge of either *in situ* element's location. For the lander, this would occur when the range is < ~30,000 km. The montgolfière would be a mobile platform that must be located prior to every flyby with telecom relay.

To maintain the link in these situations, the orbiter would maintain and update an on-board estimate of the location of each *in situ* element during the relay. This is done by periodically performing a two-axis peak scan with the HGA to locate each *in situ* element within the HGA footprint. For the lander, this will enable the link to be maintained to the minimum range of ~3,000 km at the end of the 9 hr relay period. For the montgolfière, this would enable the link to be maintained through close Titan flybys.

The montgolfière would have the ability to detect the orbiter's transmitted signal and turn its own 0.5 m HGA in the direction of the orbiter to maximize communication rates without complex (given the lack of guide-stars) on-board attitude determination.

Finally, there would be periods of ~8 days in duration when the montgolfière is not in communication with the orbiter due to occultation by Titan. The winds at the 10 km altitude at which the montgolfière is designed to float, would move the montgolfière along lines of relatively constant latitude. This allows for coarse interpolation of its position through these periods to predict windows when the montgolfière would reemerge into the orbiter's view. In general, the orbiter would be far enough away that the HGA will cover all of Titan when the montgolfière reemerges. Once the link is established, a peak scan could then be used to get a fix on the montgolfière's location.

An additional science requirement on the montgolfière is to reconstruct its location to 1 km knowledge accuracy in latitude and longitude for the interpretation of measurements taken by the montgolfière. Angular data from the orbiter's peak scan and the pointing of the montgolfière's HGA would help in this determination, but it will primarily be done via radiometric tracking employing range data and two-way Doppler from the orbiter. Post-processing correlation of the time-stamped images from the montgolfière to global Titan maps, created by TSSM in the Circular Orbit Phase, would provide even more precise knowledge of the montgolfière's position for science data analysis. This terrain-based optical navigation would also provide a way to estimate the montgolfière's position during periods when it is not in view.

Titan Aerobraking

Titan Orbit Insertion (TOI) places the orbiter into a 15,000 km by 720 km 85° inclination elliptical orbit around Titan. Over several orbits, Saturn's gravitational perturbations then raise periapsis of this orbit before pushing it lower into the atmosphere. During these atmospheric passes, drag lowers the orbit apoapsis (See Figure 8). As the periapsis altitude nears 600 km, the heating on the spacecraft reaches a peak heating of 0.23 W/cm^2, which is below the aerobraking trajectory heating threshold of 0.25 W/cm^2. This value was chosen to be roughly half of the aerobraking heating limits from other missions shown in Table 10. Before the trajectory heating threshold would be reached, a maneuver is performed to raise periapsis. This maneuver is sized such that Saturn's gravity will subsequently lower the periapsis back into Titan's atmosphere.

This phase enables many low altitude passes for *in situ* sampling of Titan's atmosphere as well as *in situ* measurement of Titan's intrinsic magnetic field below the ionosphere. Figure 9 details the altitude versus latitude coverage during this phase showing complete coverage of the southern hemisphere below 1000 km altitude. Additionally, the high apoapses at the beginning of this phase enable global monitoring of Titan for clouds and other features of the troposphere and excellent geometry for Titan limb sounding.

The aerobraking sequence is designed using an atmospheric model developed for the study by experts on Titan's atmosphere using Cassini and Huygens data. This model will be updated based on Cassini extended and extended-extended mission data prior. In addition, several low-altitude flybys during the tour shown in Table 7 provide an opportunity to directly measure the atmosphere prior to the start of aerobraking so as to confirm the Titan atmospheric models early enough to allow for adjustments to the aerobraking trajectory.

Titan's atmosphere is more stable than Mars' with a predicted 1-sigma density variation of 15% pass-to-pass compared to 30% 1-sigma for Mars. In addition, a hazard to Mars aerobraking is planet-wide dust storms that can pop up over a span of a few days and increase density by a factor of 10. Titan does not experience anything similar to these planet-wide storms, and the aerobraking operations are much more benign as a result.

In fact, atmospheric variability is a small effect in comparison to perturbations from Saturn's gravity that would raise and lower periapsis of the elliptical aerobraking orbit. Most of the 79 m/s of maintenance ΔV during aerobraking is required to counteract Saturnian perturbations. If the Aerobraking Phase were shortened to 30 days, Saturn's effect is reduced and the maintenance ΔV is reduced to only 63 m/s.

Attitude stability during aerobraking is maintained by placing the spacecraft in a passively stable attitude shown in Figure 10, which has the large drag area of the High Gain Antenna (HGA) behind the center of mass of the spacecraft like a shuttlecock. Prior to the start of aerobraking, the HGA will be placed using the current estimate of the center of mass location so as to minimize attitude transients about the stable attitude.

Figure 11 shows the portions of the spacecraft that would be exposed to the ram direction of the flow during aerobraking. The majority of this area is the HGA and the engine cover. The PMS (Polymer Mass Spectrometer) instrument has a sampling port that is aligned with the flow for science data collection.

More information on the design of the TSSM aerobraking phase may be found in a paper by Lyons and Strange.[8]

Titan Circular Orbit

After aerobraking, the orbiter enters a 1500 km circular orbit at an inclination of 85°. The 1500 km altitude was chosen because of the negligible drag at this altitude allows for long spacecraft life, while still being at a reasonable distance from the surface. However, lower altitudes are possible for reasonable amounts of orbit maintenance. As future work, this altitude will be re-examined and fine-tuned for optimal total mission science return.

The 85° inclination was chosen because it is near-polar and allows coverage of almost all of Titan's surface. By being slightly off-polar, Saturn's gravity will rotate the orbit plane. Saturn's orbit results in an apparent motion of the Sun in Titan's sky of ~9°/year. By choosing 85° as opposed to 95° inclination the orbit plane rotation will add to the Sun's apparent motion leading to a ~20°/yr motion of the Sun with respect to the orbit plane. This is a ~2.5 hr change in Local Solar Time (LST) of the orbit's descending and ascending nodes over the 20-month Titan Circular Orbit Phase.

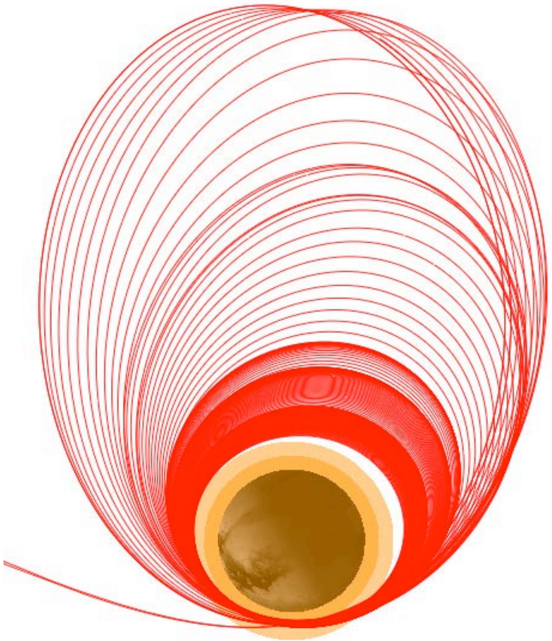

Figure 8. *Aerobraking phase orbits.*

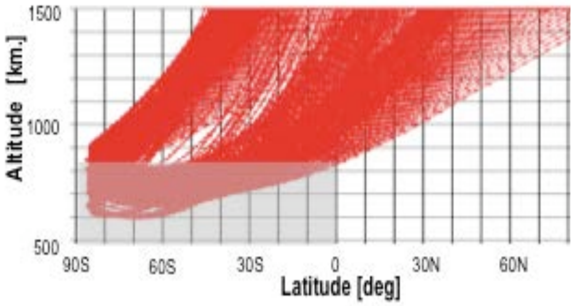

Figure 9. *Aerobraking latitude coverage*

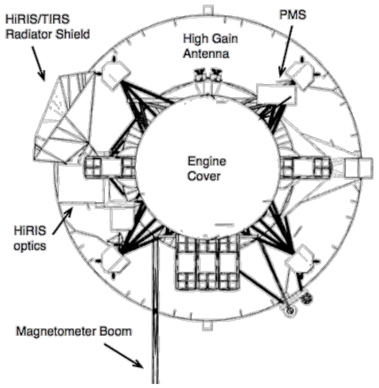

Figure 11*. View from ram direction*

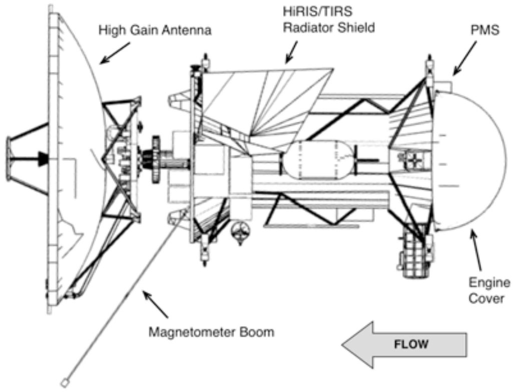

Figure 10. *Attitude during aerobraking*

Table 10. *Aerobraking Heating Limits*

Spacecraft	Heating Limit (W/cm^2)	Comment
MRO	0.55	limit due to solar panels
MGS	0.79	limit due to solar panels
Magellan	0.40	s/c not designed for aerobraking; solar panels especially sensitive
Odyssey	0.65	limit due to solar panels

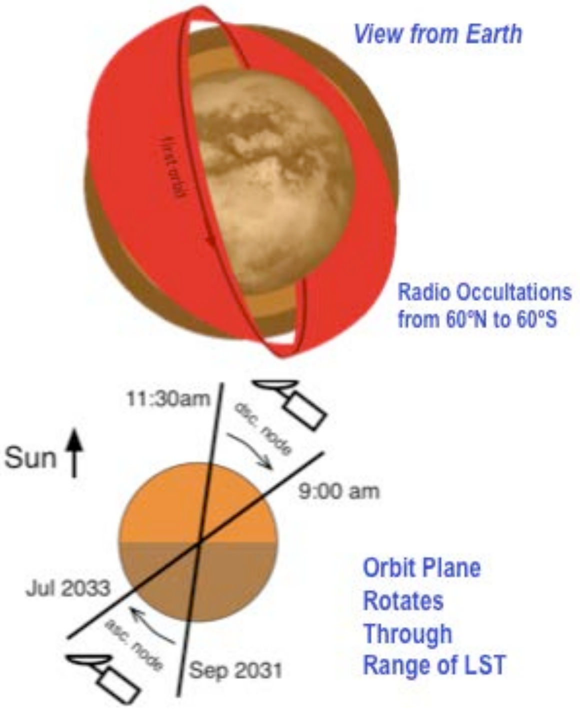

Figure 12. *Plane rotation during Titan circular orbit phase*

The orbit plane starts with a descending node at a 11:30 am LST which rotates to 9:00 am by end of mission (see Figure 12). This allows a range of Solar phase angles from low phase angles that provide high signal to noise for optical remote sensing to higher phase observations that provide greater shadowing to highlight relief. In addition, as shown in Figure 12, this plane rotation allows Titan atmospheric radio occultations at a wide variety of latitudes.

Decommissioning and Disposal

After the end of the prime mission there would be a six-month Decommissioning and Disposal Phase during which the spacecraft will impact Titan. At the end of the mission, a 15 m/s maneuver lowers periapsis to ~1340 km altitude. Perturbations from Saturn's gravity will increase the eccentricity of this orbit over a period of 4–5 months until the periapsis decreases to ~1000 km and atmospheric drag accelerates the decay. From this point, the orbit will decay and impact in about a week. Small maneuvers made before and during this final descent can move the final impact point several hundred km on Titan's surface. This enables the final impact to be targeted away from any places, identified during the mission, where liquid water may be near the surface (i.e. volcanically active areas) that would be of planetary protection concern.

Mission ΔV

Table 11 shows the mission chemical ΔV budget for both bi-prop and mono-prop along with the associated rationale for each line item. The deterministic mission ΔV has been verified by high fidelity modeling of the trajectory. The statistical ΔV is estimated, with rationales given in the table, based on Cassini and Galileo historical experience.

The ΔV in this table is that needed to implement the baseline mission design along with margin to cover values that were either estimated (e.g., statistical and mono-prop ΔV) or likely to grow as the trajectory is better optimized for science. Maneuvers that will change little as the mission design evolves need little margin (e.g., SOI, TOI, PRM). The tour ΔV, however, benefits from the margins shown to enable flexibility in the upcoming refinement of the tour design. Similarly, the aerobraking maintenance ΔV margin is to allow for flexibility in new maneuver strategies to allow better optimization for spacecraft operations. Should changes to the mission design as the project progresses require more ΔV than shown, the interplanetary SEP trajectory can be modified to provide significantly more mass to Saturn (up to 340 kg more) for longer flight times.[1,7]

Backup Launch Opportunities

The baseline mission launches in 2020 on a SEP EVEE trajectory. The primary backup launch opportunity is a 2022 EVEE gravity assist trajectory detailed in Tables 12 and 13. The 2022 backup gives the maximum xenon load (550 kg after 10% margin is added) used for sizing the SEP stage tanks.

The 2022 trajectory has a very similar chemical ΔV budget to the 2020 trajectory (see Table 11). The difference being in that SOI decreases to 689 m/s from 746 m/s. Another backup option exists six months earlier in 2021, but it arrives at Saturn the same time as the 2022 trajectory. Table 14 describes the features of other SEP trajectories in the 2018-2022 launch years such as flight time and size of SOI. All of these trajectories are assumed to use the same orbiter and *in situ* element designs, and the table shows they achieve similar mass capability for the orbiter as the baseline trajectory with lower chemical propellant loads than the baseline (i.e. the propellant would fit in the baseline tank design).

Table 11. *Mission ΔV budget.*

	Bi-Prop ΔV [m/s]	Mono-Prop ΔV [m/s]	Description
Interplanetary TCMs	4	1	Several small maneuvers needed after SEP stage release for final Saturn targeting. *SEP stage is released prior to these maneuvers.*
SOI	746	0	**Saturn Orbit Insertion** modeled as Finite Burn with gravity losses. Three trades could reduce the size of SOI: 1. Longer flight time to Saturn, 2. Longer flight time from SOI to first Titan flyby, 3. Moving ring plane crossing to gap below D-ring.
SOI-CU (3%)	22	0	**SOI Clean-Up** estimated as 3% of SOI to represent a 3-sigma case. By estimating the largest maneuver's cleanup as 3-sigma, TSSM is robust to at least one 3-sigma cleanup.
BTM	261	0	**Balloon Targeting Maneuver** modeled to deliver montgolfière to Titan entry target. Increasing the period of the initial Saturn orbit may reduce this ΔV. This could be possible without increasing the total tour duration.
BTM-CU (2%)	5	1	**BTM Clean-Up** ΔV in one or two maneuvers estimated as 2% of BTM to represent a 2-sigma case. Additional 1 m/s of mono-prop ΔV added for precision targeting. *The montgolfière is released after these maneuvers.*
PRM	309	0	**Periapsis Raise Maneuver** to set-up first Titan flyby. Increasing the period of the initial Saturn orbit may reduce this ΔV. This could be possible without increasing the total tour duration.
PRM-CU (2%)	6	0	**PRM Clean-Up** estimated as 2% of PRM to represent a 2-sigma case.
LTM	7	0	**Lander Targeting Maneuver** modeled to deliver lander to Kraken Mare.
LTM-CU	0	1	**LTM Clean-Up** estimated as 1 or 2 maneuvers totaling 1 m/s of mono-prop ΔV. *Lander is released following these maneuvers.*
ODM	110	0	**Orbiter Delay Maneuver** provides 9 hour delay from lander entry at Titan and orbiter closest approach at the end of the lander relay.
ODM-CU (2%)	2	0	**ODM Clean-Up** estimated as 2% of ODM to represent a 2-sigma case.
Tour Deterministic	40	0	Deterministic ΔV found from integrated tour trajectory. This ΔV is required primarily for targeting of Enceladus flybys. Otherwise, the tour would be nearly ballistic.
Tour Margin (50%)	20	0	This margin leaves rooms for future refinement of the tour design.
Leveraging Pump-Down	197	0	ΔV to decrease Titan V-infinity prior to TOI. This ΔV may be reduced by adding 1–2 months to the tour duration.
Beta Adjustment	25	0	ΔV needed (in two maneuvers) to achieve the proper orientation of the Titan orbit with respect to the Sun (i.e., a descending node crossing at 11:30 am LST). This ΔV could be reduced with refinements to the tour design.
Tour Phase Statistical	12	12	Estimate of the statistical ΔV needed for the entire tour phase extrapolated from the Cassini Extended Mission tour design experience. This estimate is 0.5 m/s of bi-prop and 0.5 m/s of mono-prop per targeted flyby (24).
TOI	388	0	**Titan Orbit Insertion** modeled as Finite Burn with gravity losses. This ΔV could be reduced with further refinement of the leveraging pump-down and of the aerobraking phase.
TOI-CU (2%)	8	0	**TOI Clean-Up** estimated as 2% of TOI to represent a 2-sigma case.
Aerobraking Maintenance	79	0	ΔV from simulated 2 month aerobraking design with drag and Saturn gravity. This ΔV can be reduced with a shorter Aerobraking Phase (e.g., 63 m/s for a 30 day aerobraking).
Aerobraking Margin (15%)	12	0	This margin is to maintain flexibility in the future design of the aerobraking maneuver strategy. However, aerobraking maintenance ΔV may also decrease with this refinement.
Circularization	85	0	ΔV required to raise periapsis and to circularize the orbit at the end of aerobraking. This ΔV would be reduced for a lower circular orbit. (to ~65 m/s for 1400 km or ~45 m/s for 1300 km)
Circular Orbit Maintenance	0	4	ΔV needed to maintain circular orbit from simulation with drag and Saturn gravity + 100% margin. This large margin is to maintain operational flexibility.
De-Orbit and Disposal	18	2	15 m/s for de-orbit plus additional ΔV margin to control the 6-month orbit decay.
Total	2356	21	

Table 12. *21-day launch period (2022).*

	Beginning of Launch Period	Middle of Launch Period	End of Launch Period
Date	Mar 28, 2022	Apr 6	Apr 16
C_3 [km^2/s^2]	1.44	1.40	1.44
DLA [deg]	18.8°	20.4°	20.9°
Launch Mass [kg]	6175	6175	6175
SEP ΔV (km/s)	3.33	3.33	3.33
Xenon Fuel (kg)	500	500	500

Table 13. *Interplanetary events (2022).*

Event	Date / Altitude
Launch	Mar 27–Apr 16
Begin SEP Thrusting	May 26, 2022
Earth-1	May 25, 2023 / 15770 km
Venus	Sep 19, 2023 / 5550 km
Earth-2	Jun 4, 2024 / 1550 km
Earth-3	May 9, 2026 / 600 km
End SEP Thrusting	Aug 7, 2027
SOI (689 m/s)	Sep 30, 2031

Table 14. *SEP trajectories in alternate launch years.*

Path	Launch Date	Arrival Date	FT to Saturn [y]	Launch C3 [km^2/s^2]	Launch Mass [kg] (A551)	Xenon Fuel [kg]	Saturn V_∞ [km/s]	SOI ΔV [m/s]	Chem. Fuel [kg]	Orbiter Mass [kg]
EEVEE	Jul 2018	Jan 2028	9.5	1.2	6200	500	6.20	680	2432	1705
EVEE	Jan 2019	Feb 2028	9.0	1.2	6200	500	6.20	680	2432	1705
EVEE	Sep 2020	Oct 2029	9.0	0.8	6240	445	6.66	745	2533	1703
EEVEE	Oct 2021	Mar 2031	9.4	1.4	6175	500	6.10	670	2414	1704
EVEE	Apr 2022	Feb 2031	8.8	1.4	6175	500	6.10	670	2414	1704

Trajectory Modeling Assumptions

Prior to this study, it was widely assumed that a Titan mission with an orbiter and *in situ* elements would require Titan aerocapture for the orbiter, especially with an Atlas V launch. This study use v-infinity leveraging techniques[9-10] to accomplish the TSSM objectives without aerocapture. In order to verify the correctness of these new approaches and the associated ΔV budget, the trajectory was integrated from launch to end of mission in a high fidelity force model including n-body perturbations and Titan atmospheric drag when appropriate. Forces dependant on the spacecraft design and attitude were neglected (e.g., solar radiation pressure, RPS radiation pressure, etc), but these forces are not expected significantly to change the ΔV budget or the correctness of the trajectory.

CONCLUSION

The TSSM mission design effort has resulted in an innovative end-to-end trajectory that achieves all science objectives[1] using techniques that have all been demonstrated on previous planetary missions. Using an Atlas V (551) launch vehicle and the aid of a SEP stage, the TSSM architecture is capable of delivering two in situ elements, a montgolfière hot air balloon (600 kg allocation) and a lake lander (190 kg allocation) as well as a flagship-class orbiter (1613 kg dry mass with 35% system margin) to Titan. The mission design also includes an innovative tour through the Saturn system that captures Saturn and Enceladus level 1 requirements. As a result of the 2008 TSSM study, it is clear that attractive solutions exist for a comprehensive mission to both Titan and Enceladus. Future work will continue to explore such options.

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