Trajectories for Flyby Sample Return at Saturn's Moons

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Ballistic trajectories are computed which would enable a sample return mission to Titan or Enceladus without capturing, descending, or landing. The low-cost mission concept utilizes a free return trajectory that also involves a close flyby of the moon. This work extends the concept, and related trajectory analysis methodology, previously applied to a Europa mission. Specifically, a broad search algorithm is employed to systematically locate potentially feasible itineraries over an entire Saturn period. High-quality approximate solutions are then optimized to be continuous using high-fidelity dynamics. Techniques and software from the Europa analysis were readily adapted and able to find numerous mission enabling trajectories. A direct mission to Titan is possible with flight time under 16 years and Earth-relative speeds below 11.0 km/sec. The VEEGA option is shown to substantially reduce launch C_3, but flight times exceed 21 years. Unfortunately, an Enceladus mission requires a flight time of 25 years or more, and incurs fairly high relative speeds. Nevertheless, an optimized reference mission is computed.

I. Introduction

Outer planet icy moons are among the highest priority targets for exploration, in part because of their great astrobiological potential.[1] In this paper trajectory analysis for a flyby sample return mission concept, previously studied for Europa, is extended to Saturn's moons Titan and Enceladus. Like Europa, Enceladus is known to contain a subsurface ocean of liquid water, and is observed to eject this material into space in the form of geysers or plumes. The Cassini spacecraft recently discovered the presence of various organics in the plumes.[2] Unlike Enceladus and Europa, Titan has a thick atmosphere which shrouds its surface. Nevertheless, hydrocarbons (Tholines) and various pre-organic complex molecules have been discovered in the upper-most reaches of this atmosphere.[3]

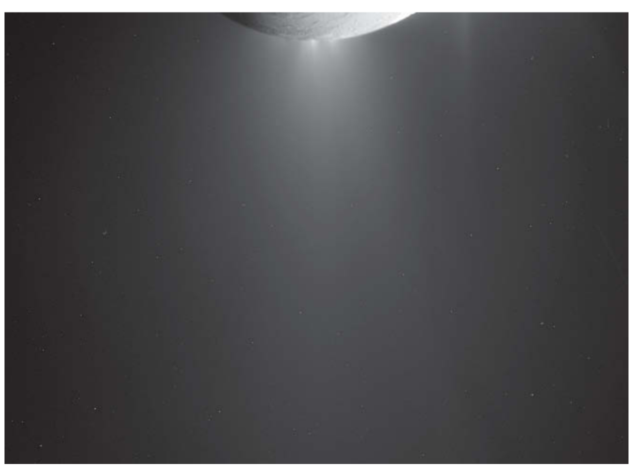

Figure 1: Plumes at south pole of Enceladus. SOURCE: NASA/JPL/Space Science Institute

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The scientific value of a returned sample cannot be overstated. The Stardust sample alone has resulted in more than 50 publications per year since it was returned.[4,5] Relative to the adaptive, sophisticated, and synergistic techniques available on Earth, it is clear that even the most expensive robotic lander is relatively handicapped in the subtle task of identifying extraterrestrial "life". A variety of proposed concepts have aimed to achieve an Enceladus plume sample return, including a $1B flagship study[6], and two Discovery mission proposals LIFE[7] and ELF.[8] All of these concepts involve expensive capture and departure maneuvers at Saturn. In the case of LIFE, this amounts to over 3 km/sec of ΔV. Flyby sample return missions using a free return, have been proposed at Europa[9] and for the Martian atmosphere.[10]

Here an alternative and novel mission concept is analyzed to return a sample from either Titan or Enceladus, without capturing at Saturn. Instead, ballistic free return trajectories are sought which also incur a close encounter of the icy moon. The spacecraft could sample a plume (or upper atmosphere) during the hyperbolic flyby. This concept has been considered for Europa, using an impactor to generate the debris plume, something not necessarily required at Enceladus (definitely not for Titan).[9]

The method and algorithms used in this study to locate and optimize potential trajectories, is a direct extension of work previously applied to Europa.[11] To summarize, a systematic broad search is used to first determine potential ballistic free return itineraries (Earth-Saturn-Earth in this case). Then Venus/Earth flyby sequences are (optionally) computed to connect with previously determined direct free return solutions. Finally, the patched-conic solutions are filtered and high-quality solutions are differentially corrected with high-fidelity dynamics, realistic constraints, and precise targeting of the sample collection flyby. The method restricts attention to ballistic trajectories, and does not consider ΔV leveraging maneuvers, aerobraking, or inertial thrusting.

II. Flyby Sample Return Mission

The fundamental mission scenario is that a ballistic Earth-Saturn-Earth trajectory is followed, such that the Saturn gravity assist returns the spacecraft to Earth (without deterministic maneuvers). The geometry of the free return is restricted such that a close flyby of either Titan or Enceladus may also occur. The concept was first introduced as a proposed Discovery-class mission to Europa.[9] A kinetic impactor was envisioned as being jettisoned from the main spacecraft to impact Europa, and thereby create the plume to be sampled. When considering Enceladus, it may be possible to fly through naturally occurring plumes (near the south pole), thereby eliminating the need for an impactor. For Titan, the upper atmosphere would be targeted. In either case, the collection mechanism is tentatively considered to be Aerogel (similar to Stardust), however alternate mechanisms are possible.[9]

Silica aerogel has substantial heritage, proving itself a successful mechanism for attaining samples during flyby encounter. Moreover, extensive laboratory experiments finds Aerogel can suitably and reliably collect particles of varying density, porosity, and size at relative speeds up to 7 km/sec, and likely higher.[12] Stardust Wild 2 samples showed that an amino acid can be captured and retained in a flyby mission without special preservation techniques.[13]

III. Broad Search Approach

A broad search is devised to compute potentially feasible (and ballistic) patched conic trajectories. The trajectories consist of multiple Lambert arcs (legs), joined by hyperbolic flybys at the encounter body (nodes).* A detailed description of the search methodology is provided in Reference 11, but an overview is repeated here for clarity.

Initially, direct Earth-Saturn-Earth free returns are computed. But in order to reduce launch C_3, particular outbound Venus/Earth flyby sequences are considered. Unfortunately, the use of a Jupiter gravity assist (outbound or inbound) is not available for launches after 2019. The option of using Jupiter does not occur again until the latter part of the 2040 decade. For this reason, flybys of Jupiter are not included. The following assumptions are made:

*Here encounter indicates an intermediate flyby, Earth launch, or Earth entry.

1. Legs include only the gravity of the Sun.
2. Hyperbolic flybys include only the gravity of the encounter planet.
3. Planetary positions are taken from JPL's DE430 and Saturnian satellite positions from SAT375.[14]
4. Powered flybys, consisting of a single 'small' impulse at periapsis, are permitted (later removed in optimization).

The primary search variables are the encounter epochs, but the type of Lambert arc (number of revolutions and fast/slow case) are secondary search variables. The search is exhaustive but uses constraints to eliminate or filter poor combinations as early as possible (doing so reduces the computational complexity). The following feasibility conditions (or constraints) are enforced:

1. Nearly equal v_∞ magnitudes at nodes (equivalently small impulse magnitude at the node periapsis).
2. Minimum altitude at every node.
3. Relatively small v_∞ magnitude at every node.
4. Minimum range from Saturn outside the F-ring, but not far beyond the orbit radius of the target moon.
5. Radial distance at the nodal intersection of the trajectory with the target moon's orbit plane (referred to as the node radius) must be close to target moon's semi-major axis.

These conditions are subjective and therefore engineering judgment and experience is used to quantify them. The following notation is adopted for the searches. Each node is specified by an encounter periapsis time, where

$$\tau_N < \tau_{N-1} \cdots < \tau_2 < \tau_1 < t_0 < t_1 < t_2$$

The Earth-Saturn-Earth free return nodes are denoted t_0, t_1, and t_2, with flight times of Δt_{01} and Δt_{12}. Any Venus/Earth nodes (before) t_0 are denoted by τ_j, where $j = 1$ is the last encounter before t_0. Flight times for these legs are $\Delta\tau_{ij}$ (where $i = j - 1$). Interior nodes have relative velocity vectors $\mathbf{v}_\infty^-$ (incoming) and $\mathbf{v}_\infty^+$ (outgoing), and a maximum allowable discontinuity in magnitude is specified as $(\Delta v_\infty)_{\max}$. Also, $(v_\infty)_{\max}$ denotes an upper bound for v_∞ at a given node. Saturn periapsis radius r_p^s is constrained to be between $r_{\min}^s$ and $r_{\max}^s$, and the flyby altitude at other nodes a_p is constrained to be above $a_{\min}$. Finally, the node radius (at Saturn) r_{node}^s is constrained to be no further than Δ_{node} from the target moon semi-major axis r^*.

When Venus/Earth sequences are considered, the searches are deemed indirect since they are initialized from a list of previously computed direct solutions. The search then progresses backwards in time, by selecting the flight times $\Delta\tau_{ij}$. The algorithm for this (indirect) search is outlined in Reference 11.

A. Lambert's problem evaluation

The general solution to Lambert's problem, for a given flight time, admits four solutions corresponding to combinations of prograde/retrograde and fast/slow (or long/short). Fast/slow cases are also referred to as type 1 and type 2 in the literature. Russell[15] gives an excellent detailed summary of the problem. Only prograde transfers are considered here, and only zero revolution transfers are considered for the direct free return search.

B. Flyby Evaluation

Upon solving Lambert for each leg in the search, powered hyperbolic flybys at the encounter nodes are computed. These are necessary to evaluate constraints, and the hyperbolic orbits are used as part of the initial guess when differentially correcting to achieve continuity. There are two cases to consider:

1. The end nodes of launch and re-entry at Earth. There is a single relative velocity vector $\mathbf{v}_\infty$.
2. Interior nodes, where there is both an incoming $\mathbf{v}_\infty^-$ and an outgoing velocity vector $\mathbf{v}_\infty^+$.

In both cases, the periapsis state is constructed at the epoch t_i (or τ_j), corresponding to the adjacent leg(s) start/end time. For the first case, the minimum inclination departure/arrival orbit is selected with periapsis altitude of 100 km. The inclination is equal to the magnitude of the $\mathbf{v}_\infty$ asymptote declination. The inclination, $\mathbf{v}_\infty$, and periapsis altitude are sufficient to construct a state, and propagate the conic orbit. The orbit is propagated until it reaches the sphere of influence. Reference 16 provides an analytical expression for this time.

For the second case, small differences between v_∞^- and v_∞^+ are allowed during the broad search. The expectation being that small differences can later be optimized to zero, yielding ballistic flybys. During the broad search, powered flybys are constructed with a single tangential impulse at periapsis.[17] Such a maneuver is often sub-optimal, however, the guess suffices for filtering poor solutions via constraint evaluation. The transfer angle is known

$$\delta = \langle \mathbf{v}_\infty^-, \mathbf{v}_\infty^+ \rangle \tag{1}$$

The periapsis radius r_p is solved iteratively[†]

$$\sin^{-1}\left(\frac{\mu}{\mu + r_p v_\infty^-}\right) + \sin^{-1}\left(\frac{\mu}{\mu + r_p v_\infty^+}\right) = \delta \tag{2}$$

Once r_p is known, the periapsis speeds before and after the impulse are

$$v_p^- = \sqrt{v_\infty^- + \frac{2\mu}{r_p}} \qquad v_p^+ = \sqrt{v_\infty^+ + \frac{2\mu}{r_p}} \tag{3}$$

Energy and eccentricity before and after maneuver are readily derived. Since the maneuver is tangential, motion occurs in a plane containing the two asymptotes and the B-plane vector $\mathbf{B}$. The B-plane is used to resolve the plane of motion[18], and is depicted in Figure 2. The orthogonal set of B-plane unit vectors,

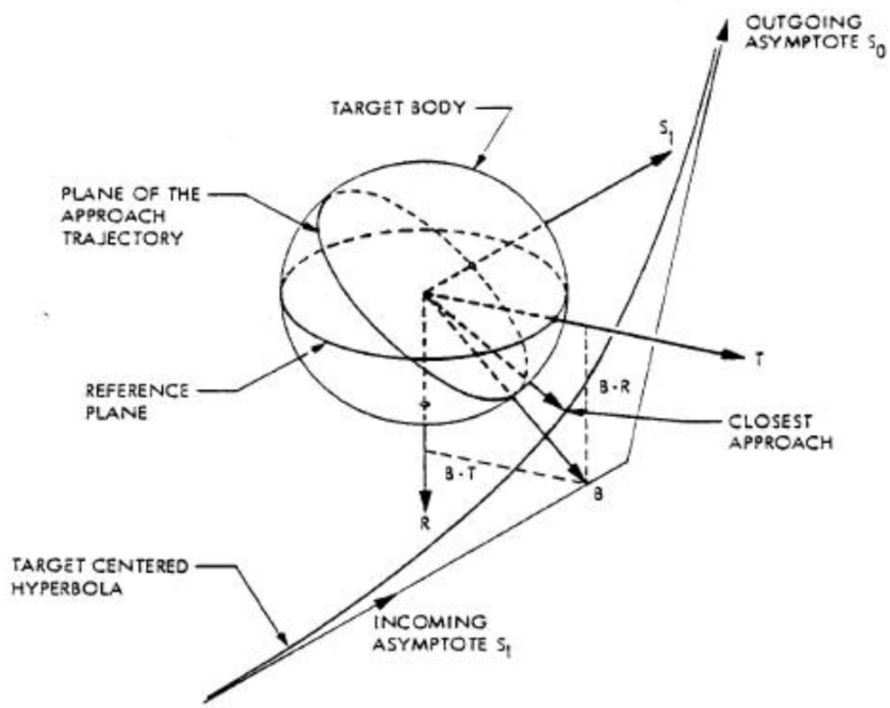


Figure 2: B-plane geometry

[†]This allows subsurface solutions, but those are handled by the $r^j_{\min}$ and $a_{\min}$ constraints.

defined in a body-centered equatorial plane are

$$\hat{S} = \frac{\mathbf{v}_\infty^-}{v_\infty^-} \qquad \hat{T} = \frac{(\mathbf{v}_\infty^-/v_\infty^-) \times \hat{k}}{\| (\mathbf{v}_\infty^-/v_\infty^-) \times \hat{k} \|} \qquad \hat{R} = \hat{S} \times \hat{T} \tag{4}$$

Where $\hat{k}$ is the unit vector of the pole $(0, 0, 1)$. The flyby bends the excess velocity vector such that the projection of $\mathbf{v}_\infty^+$ onto the B-plane is along the $-\mathbf{B}$ vector. Therefore, the angle of $\mathbf{B}$ relative to $\hat{T}$ is computed as

$$\theta_B = \text{atan2}(\frac{\mathbf{v}_\infty^+}{v_\infty^+} \cdot \hat{R} \ , \ \frac{\mathbf{v}_\infty^+}{v_\infty^+} \cdot \hat{T}) - \pi \tag{5}$$

With θ_B, states at periapsis (before and after maneuver) may be formed. These states are propagated forward and backward in time from periapsis to the sphere of influence crossing.

IV. Broad Search Results

For all searches, a full Saturn period with t_0 ranging from 2020 through 2049 is (somewhat arbitrarily) considered. To characterize solution families an initial search was performed over a very broad range of flight times, using 2030 as the launch year, and with loose constraints on node and Saturn periapsis radius. With potentially feasible families identified, the full Saturn period searches are executed separately for Titan and Enceladus.

A. Free Return Families

Figure 3 shows the relation between Saturn periapsis radius and total flight time for direct free return solutions found from the very broad search. Analogous to findings with Europa[11], there are two distinct solution families for each moon, a fast (short flight time, Type I) and a slow (long flight time, Type II). Enceladus orbits at a mere 238,000 km from Saturn, and therefore only points at the bounds of the horizontal axis in Figure 3 can achieve an Enceladus flyby. Titan orbits around 2.2E6 km, and so its fast family has flight time of 7-9 years (slow family 15-19 years).

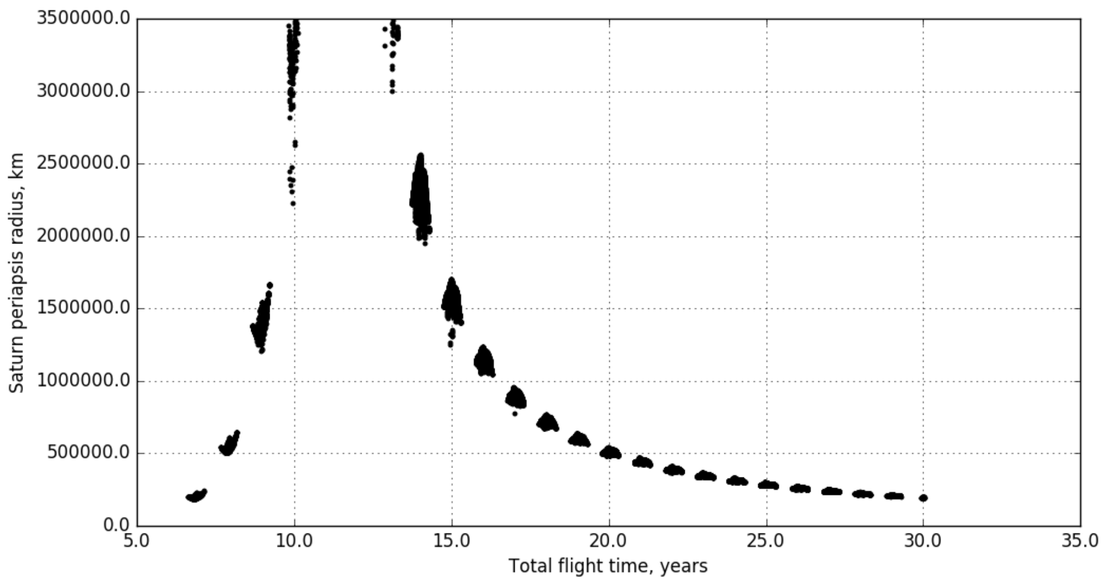


Figure 3: Direct free returns for t_0 in the year 2030: periapsis radius versus flight time

Unfortunately, the fast family trajectories approach Saturn opposite the direction of moons' orbital motion, and hence incur extremely high speeds relative to the moon. A fast family solution flyby is depicted in Figure 4. Consistent with Europa results, the fast family trajectories are not useful for this mission concept. Characteristic slow family trajectories for Titan and Enceladus are shown projected on the ecliptic plane in Figure 5. Flight times are 16 years and 25 years for the two cases, respectively.

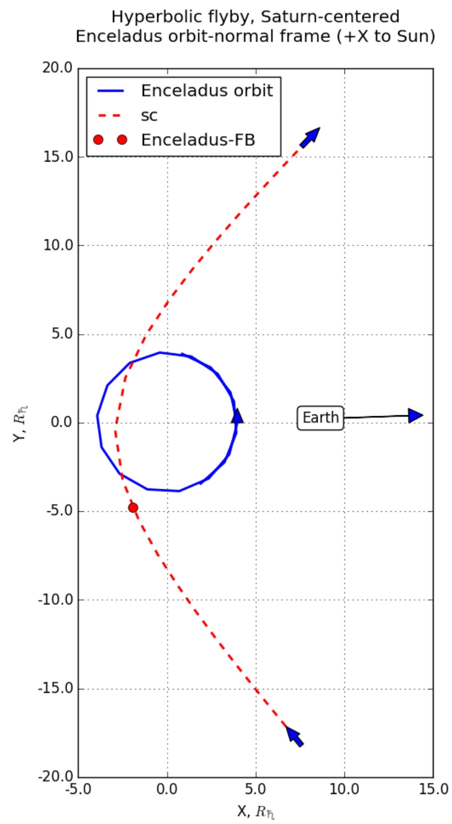
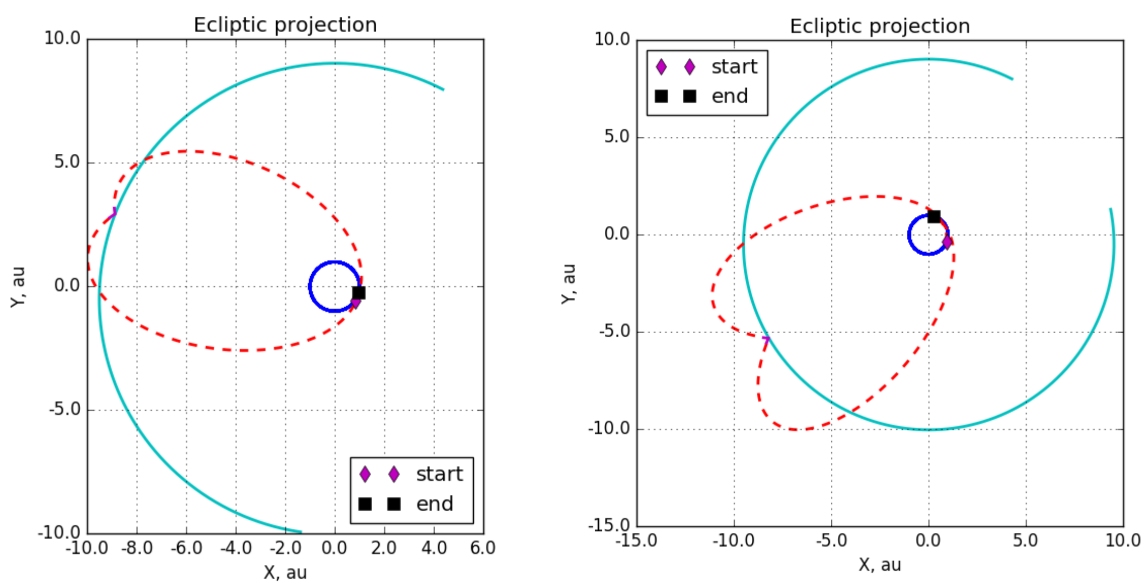


Figure 4: Saturn flyby for a fast family trajectory



(a) Titan

(b) Enceladus

Figure 5: Direct free return trajectory examples

B. Feasible Direct Free Returns targeting Titan

Based on initial findings, a full Saturn period search was initiated, using the parameter ranges and constraints listed in Table 1. The variation in periapsis radius at Saturn with respect to t_0 is illustrated in Figure 6, and a summary of the results is given in Table 2.

Table 1: Titan direct free return broad search parameters

	Min.	Max.	Step
t_0	1-JAN-2020	1-JAN-2050	10 day
Δt	2500 days	3500 days	10 days
Launch $(v_\infty)_{\max}$	-	16.0 km/sec	-
Return $(v_\infty)_{\max}$	-	15.0 km/sec	-
$(\Delta v_\infty)_{\max}$	-	100 m/sec	-
r_p^s	1.4E5 km	1.222E6 km	-
Δ_{node}	-	50000 km	-

There are many more solution options near the start of the cycle (early 2020s), although the low periapsis solutions correlate with longer flight time. Moreover, for t_0 between 2033 and 2043 solutions with flight time below 17 years become infeasible (otherwise 16 year option is available). Numerous solutions are located which have launch v_∞ less than 11 km/sec. By comparison the minimum v_∞ for a direct launch to Saturn is just over 10 km/sec.

Table 2: Titan direct free return results over full Saturn period

	Min.	Max.
Total flight time	14.94 years	19.11 years
Saturn v_∞	5.99 km/sec	7.45 km/sec
Earth departure v_∞	10.54 km/sec	15.99 km/sec
Earth return v_∞	10.40 km/sec	14.99 km/sec

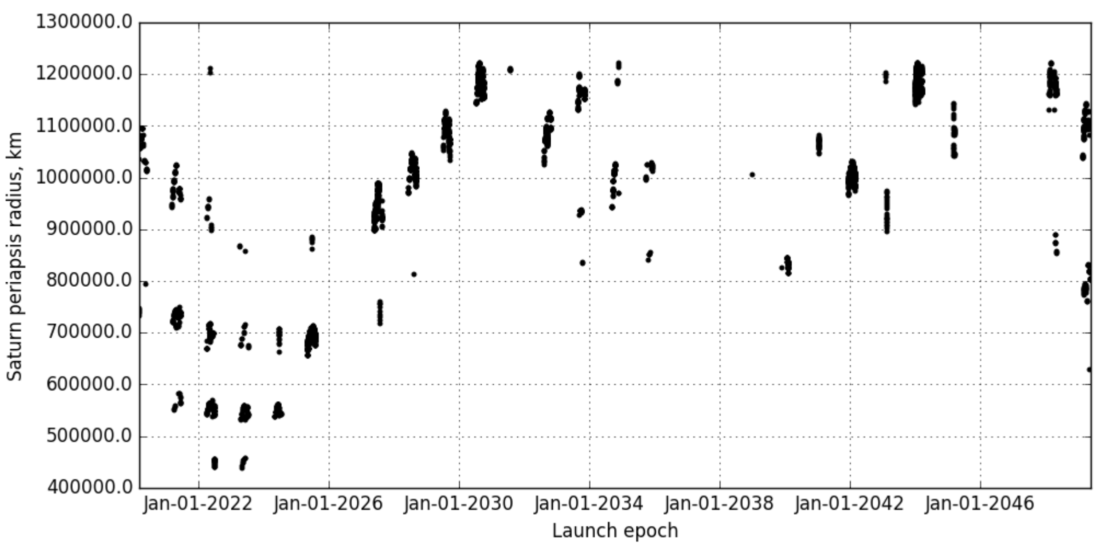


Figure 6: Titan direct free return results: periapsis radius versus t_0

C. Feasible Direct Free Returns targeting Enceladus

Table 3 lists parameters used in locating direct solutions targeting Enceladus. As shown in Figure 7, unfavorable geometry for t_0 between 2031 and 2034 leads to an absence of feasible trajectories. As summarized in Table 4, flight times range from just under 24 years (relatively large Saturn periapsis radius) up to 30 years.

Table 3: Enceladus direct free return broad search parameters

	Min.	Max.	Step
t_0	1-JAN-2020	1-JAN-2050	10 day
Δt	4000 days	5500 days	10 days
Launch $(v_\infty)_{\max}$	-	20.0 km/sec	-
Return $(v_\infty)_{\max}$	-	18.0 km/sec	-
$(\Delta v_\infty)_{\max}$	-	100 m/sec	-
r_p^s	1.4E5 km	2.38E5 km	-
Δ_{node}	-	50000 km	-

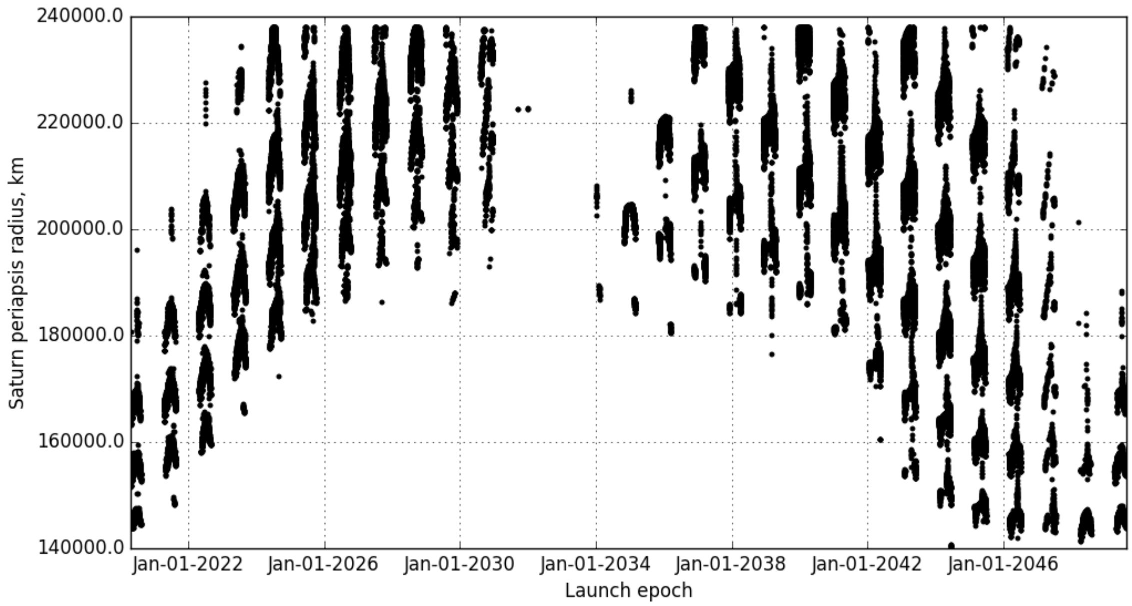


Figure 7: Enceladus direct free return results: periapsis radius versus t_0

There are many solutions with v_∞ less than 14 km/sec at Earth launch and reentry. However, very long mission durations necessary to ballistically target Enceladus, makes for an overall less appealing concept. Because of the long flight times, Venus/Earth sequences are not considered for missions targeting Enceladus.

Table 4: Enceladus direct free return results over full Saturn period

	Min.	Max.
Total flight time	23.79 years	30.06 years
Saturn v_∞	7.64 km/sec	9.35 km/sec
Earth departure v_∞	10.74 km/sec	19.99 km/sec
Earth return v_∞	10.68 km/sec	17.99 km/sec

D. Missions targeting Titan with Venus/Earth Flybys

The sequences EVESE (Earth-Venus-Earth-Saturn-Earth), EVEESE, and EVVESE were searched broadly using the parameters in Table 5, and starting from a subset of direct solutions summarized in Table 2. The sequence EVESE produced no solutions, even when considering the full Saturn period. EVVESE produced very few solutions, characterized by low-altitude flyby at Earth and the first Venus flyby. EVVESE tend to have longer flight time and launch energy than EVEESE solutions, and therefore the former are of little value. This is the same result found when considering Europa.[11]

Table 5: Titan indirect free return broad search parameters

	Min.	Max.	Step
revs	0	3	-
Δt	100 days	2000 days	5 days
Launch $(v_\infty)_{\max}$	-	11.0 km/sec	-
$(\Delta v_\infty)_{\max}$	-	100 m/sec	-
$a_{\min}$	100 km	-	-

Table 6: Titan EVEESE broad search results for t_0 in the year 2030

	Min.	Max.
Total flight time	21.46 years	29.87 years
Saturn v_∞	6.20 km/sec	6.54 km/sec
Earth departure v_∞	3.91 km/sec	10.99 km/sec
Earth return v_∞	11.23 km/sec	14.99 km/sec

The EVEESE can provide significant launch C_3 reduction, but with increased flight time. Solutions found for t_0 in the year 2030 are summarized in Table 6. An example EVEESE trajectory is depicted in Figure 8. This 22.4 year long mission has a very low launch v_∞ of 3.92 km/sec, and the Earth return v_∞ is 11.39 km/sec. It consists of a 2-rev/slow transfer (type 2) of 650 days to Venus, followed by a 0-rev transfer (490 days), a 1-rev/slow transfer of 1205 days back to Earth, and finally the ESE free return.

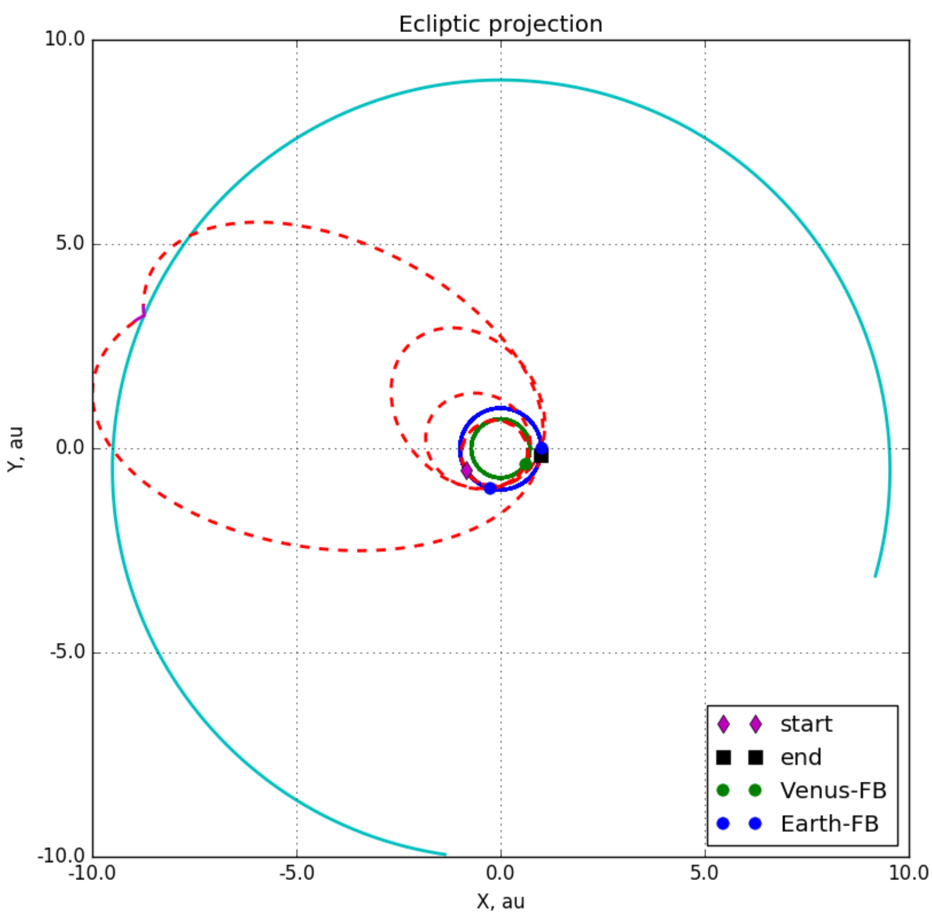


Figure 8: Titan EVEESE trajectory example

V. Optimized Reference Missions

The assumptions in computing the broad search trajectories yield non-zero state discontinuities between legs and flybys, and a number of important error sources. Additionally, the Titan/Enceladus flyby has yet to be targeted nor is the gravity of that body considered. A differential correction method is employed to converge the broad search solutions with complete continuity, and while achieving Earth launch/entry conditions, and a low-altitude flyby of the target moon. A two-step continuation (homotopy) is used. Step 1 includes the gravity of Earth, Venus, Saturn, and Sun and achieves a moon flyby below 10,000 km altitude. Step 2 adds gravity of all planets, the Moon, and the ten largest moons of Saturn. This step reduces the flyby altitude below 1000 km. In the final step of convergence, the following constraints are enforced.

1. Minimum/maximum periapsis altitude at the target moon.

2. Periapsis altitude of 100 km and 0.0 deg flight-path angle at Earth launch and re-entry.

3. Overall trajectory continuity to a tolerance of 1.0E-3 km in position and 1.0E-6 km/sec in velocity.

Additional details of the optimization approach are available in Reference 11.

A. A direct mission to Titan

An optimized direct free return reference mission is summarized in Tables 7-8. This 16 year mission, has the Titan flyby occurring about 10 hours prior to Saturn closest approach. Although, the Earth v_∞ values are somewhat large, the re-entry speed is well below that of Stardust.[19] This direct free return option has the advantage of a relatively short mission duration. Flyby closest approach is at longitude of +110 deg and latitude +40 deg, a location in sunlight and with line-of-sight to Earth.

Table 7: Titan ESE optimized reference mission flight times

Leg	E → S	S → E
Flight time, days	2760	3121

Table 8: Titan ESE optimized reference mission encounter summary

Body	Epoch, UTC	Altitude, km	v_∞, km/sec
Earth	17-AUG-2030 00:00:00	100	11.31
Titan	07-MAR-2038 03:26:51	500	5.60
Saturn	07-MAR-2038 13:12:46	1094725	6.41
Earth	22-SEP-2046 00:00:00	100	11.38

A real mission may wish to target a particular flyover location. There is generally a cost associated with the alternate flyby geometry (causing the flight through the Saturn system to be non-ballistic). Such costs are not addressed here, but a method for computing them parametrically is presented in Reference 11, for Europa.

B. An EVEESE reference mission to Titan

Additionally, the high-quality indirect trajectory shown in Figure 8, using an Earth/Venus flyby sequence, is optimized. The optimized mission is summarized in Tables 10-9. For this 22.4 year reference mission, the Titan flyby occurs less than 1 hour after Saturn periapsis.

Table 9: Titan EVEESE optimized reference mission flight times

Leg	E → V	V → E	E → E	E → S	S → E
Flight time, days	657	494	1207	2688	3150

Table 10: Titan EVEESE optimized reference mission encounter summary

Body	Epoch, UTC	Altitude, km	v_∞, km/sec
Earth	13-APR-2024 00:01:56	100	4.40
Venus	29-JUN-2026 15:38:51	552	8.29
Earth	07-JUN-2027 04:25:03	3393	13.54
Earth	26-SEP-2030 05:47:04	760	13.52
Saturn	04-FEB-2038 05:01:10	1094725	6.41
Titan	04-FEB-2038 05:47:04	500	5.07
Earth	20-SEP-2046 00:00:00	100	11.39

C. A reference mission to Enceladus

An optimized reference mission is depicted in Figure 9 and summarized in Tables 12-11. This 25 year mission, has Enceladus flyby occurring around 1 hour after Saturn closest approach. The long flight time and relatively high encounter speeds make this concept far less appealing for Enceladus, compared to Titan and Europa.

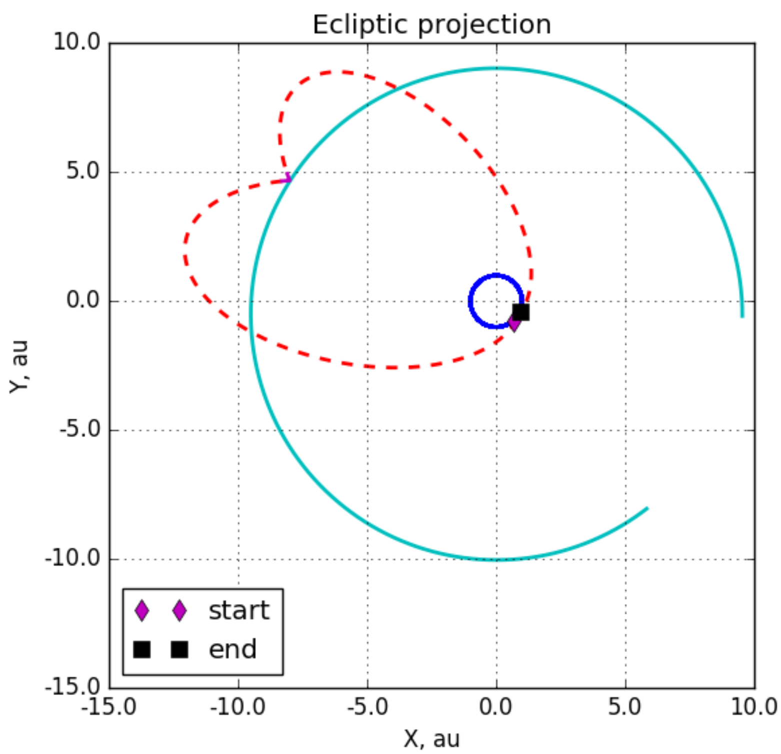


Figure 9: Enceladus reference mission trajectory

Table 11: Enceladus optimized reference mission flight times

Leg	E → S	S → E
Flight time, days	4245	4930

Table 12: Enceladus optimized reference mission encounter summary

Body	Epoch, UTC	Altitude, km	v_∞, km/sec
Earth	27-JUL-2025 22:40:19	100	11.09
Saturn	11-MAR-2037 22:31:30	165120	8.07
Enceladus	11-MAR-2038 23:41:55	100	10.03
Earth	10-SEP-2050 00:00:00	100	11.18

VI. Conclusions

This work demonstrates numerous ballistic trajectory options to enable a near-term sample return mission to Titan or Enceladus at the budget level of a Discovery or New Frontiers class mission. A concept previously considered and proposed for Europa has been extended to consider these alternate targets. Unfortunately, long flight times associated with an Enceladus mission are likely prohibitive. A Titan mission would also be of long duration (compared to a Europa mission), particularly if there is a need to reduce the launch energy.

Future work should consider Jupiter flyby and/or deterministic maneuvers as a means to reduce overall flight time. This is particularly important for Enceladus; however, the free return geometry may ultimately lead to very large maneuvers to achieve the reduction. The scientific yield of this interesting mission concept might be supplemented by targeting flybys of main-belt or Trojan asteroids during the long Saturn-Earth legs. This work is constrained to be ballistic, and so further studies may consider aerobraking or leveraging maneuvers to reduce flight time and/or encounter speeds.

Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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