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BROAD SEARCH SOLAR ELECTRIC PROPULSION TRAJECTORIES TO SATURN WITH GRAVITY ASSISTS

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Solar electric propulsion (SEP) trajectories to Saturn using multiple gravity assists are explored for the joint NASA and ESA Titan Saturn System Mission study. Results show that these new trajectories enable greater performance compared to chemical propulsion with similar gravity assists or SEP without gravity assists. This paper describes the method used in finding these interplanetary trajectories and examines variations in the performance for different SEP systems, flight times, and flyby sequences. The benefits of the SEP trajectories for a mission to Saturn are also discussed.

INTRODUCTION

Solar electric propulsion (SEP) trajectories with multiple flybys allow us to send more mass to Saturn than chemical trajectories. Results in this paper shows that these trajectories enable greater performance compared to chemical only propulsion with similar gravity assists or SEP without gravity assists. The recent mission concept study between NASA and ESA, the Titan Saturn System Mission (TSSM), explores these high mass performing SEP trajectories as its interplanetary transfer. TSSM would launch in 2020, consisting of an orbiter, a montgolfière balloon, and a lake lander, and would perform multiple flybys of Enceladus and Titan before going into orbit around Titan. The SEP system, uses as a SEP stage, is to deliver approximately 5000 kg to Saturn, which does not include the mass of the stage.

The approach of using flybys combined with electric propulsion to transfer to the outer planets is not new, previous investigations includes Atkins[1], Sauer[2], Kawaguchi[3], and Williams[4]. 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. The design procedure is composed of two main steps: 1) perform a broad search of potential gravity assist sequences and flyby times, then 2) optimize a large number of SEP trajectories using the results of step 1 as initial guesses. The paper will describe the approach in detail.

MISSION DESCRIPTION

The TSSM is to launch between 2018-2022 with a total maximum mission duration of 14 years, which includes 4 years around Saturn and Titan. If the interplanetary transfer were to exceed 10 years then science during the Titan orbit phase would need to be shortened. In addition, it is desired to have launch opportunities for 5 consecutive launch years (2018-2022).

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The TSSM would launch on an Atlas V 551, but results for the Delta-IV Heavy will be presented for comparison purposes. The TSSM consists of an orbiter, a montgolfière balloon, and a lake lander. The orbiter will be a NASA provided orbiter (1613 kg dry mass and 4141 kg wet) and ESA is to provide the two *in situ* payloads (833 kg total). The total mass of the TSSM flight system excluding the SEP stage and the Xenon propellant is 4974 kg. The SEP stage wet mass for the baseline mission is a 2-NEXT engine system with 15 kW solar array power is 1229 kg.

In this study we had a target delivery mass to Saturn of over 5000 kg. The Atlas V 551 can deliver approximately 6300 kg to a C_3 of zero. If we are to deliver 5000 kg to Saturn using the Atlas V this leaves less than 1300 kg for the SEP stage unit. In a chemical only variant, it would be difficult to deliver the same 5000 kg to Saturn because of the required higher launch C_3 (11–19 km^2/s^2 for a launch between 2018–2022 as compared to 0.6–1.4 km^2/s^2 for SEP trajectories) for transfer times less than 10 years.

After arriving at Saturn the orbiter will perform a Saturn-orbit-insertion (SOI) maneuver to capture around Saturn. This will be followed by 2 years orbiting Saturn with flybys of Titan and Enceladus. Afterwards, the orbiter will insert into an orbit around Titan for another 2 years.

BROAD SEARCH FOR POTENTIAL TRAJECTORIES

As a first step, we are to generate a comprehensive list of all reasonable gravity assist sequences to Saturn. For a sequence to be considered reasonable, the gravity-assist bodies need to be in roughly the right location so that the trajectory continues with propulsive maneuvers of no more than 3 km/s. The fine-tuning of the flyby dates and application of thrust arcs is performed at a later step using an optimizer.

Because the broad search process considers billions of sequences, a relatively simple (and computationally efficient) trajectory model is employed. A single trajectory can be described by a sequence of flyby bodies and encounter times, with Lambert fits providing the incoming and outgoing velocities at the bodies. The resulting trajectory requires ΔV at the flyby bodies, where the ΔV is a function of the incoming and outgoing V_∞ and the minimum allowable flyby radius. The most computationally efficient calculation places the maneuver at the asymptote, which is usually not ΔV optimal but works well in the context of a broad search. While the resulting trajectory contains conic arcs connected by impulsive maneuvers, it provides a reasonable initial guess for optimization with low-thrust arcs and ballistic flybys.

Just as a string of encounter bodies and dates define a single trajectory, a series of multiple bodies and dates at each encounter provides a set of trajectories. The important distinction is that the number of trajectories does not need to match the number of body/time combinations at each encounter. For example, there could be thousands of gravity assist sequences in the inner solar system that all converge to only a handful of Jupiter flyby dates before reaching Saturn. In this case thousands of unique trajectories are composed of different combinations of similar legs, and a small set of discrete body/time combinations sufficiently defines the entire range of trajectories. Figure 1 provides a schematic of the process used to create a large set of trajectories. Consider a two-flyby sequence to Saturn that allows Venus, Earth, or Mars to be either flyby. If a desired launch year is specified, then twelve discrete dates provide resolution for launching in a particular month. The resolution on the dates only needs to be fine enough to point the optimizer to a unique solution. Similarly twelve discrete dates for all of the subsequent encounters create a design space from which to build a large number of combinations. In this case 186,624 [12 * (3*12) * (3*12) * 12] trajectories are possible, but at most 2,160 [12*(3*12) + (3*12)*(3*12) + (3*12)*12] Lambert fits are computed, which dramatically reduces the computational effort. Thus as encounters are added, the number of possible combinations grows exponentially, while the computation time exhibits a more linear growth.

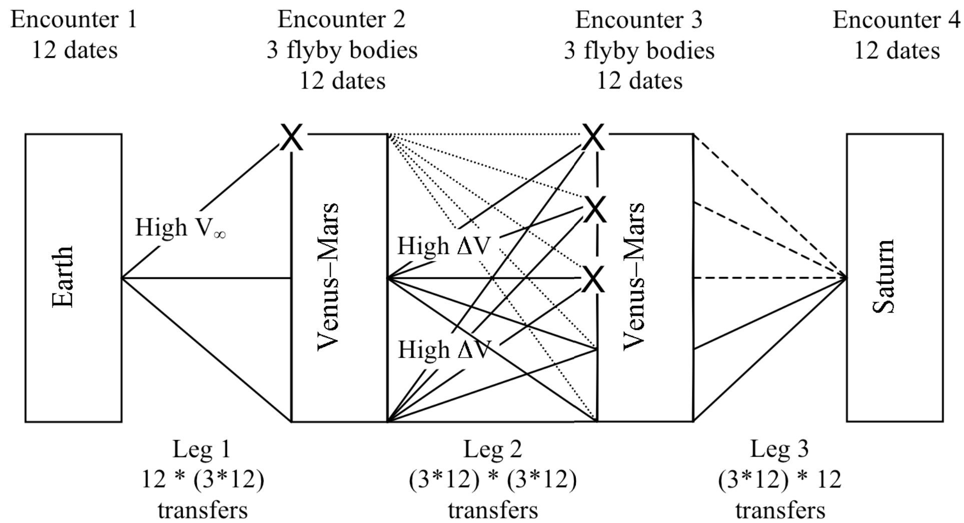

Figure 1. A broad search with discrete encounter dates provides many possible flyby combinations with a limited number of trajectory calculations. Body/date combinations at encounter 2 that do not provide low V_∞ at encounter 1 are eliminated, reducing the number of transfers for leg 2 (dotted lines). Similarly, body/date combinations at encounter 3 that do not provide low ΔV at encounter 2 are eliminated, reducing the number of transfers for leg 3 (dashed lines).

Moreover, filtering results on V_∞ and ΔV between legs reduces the number of computations significantly. For example, if the Earth departure V_∞ must be below some value, then all of the body/time combinations at encounter 2 that do not provide low departure V_∞ at encounter 1 may be removed once leg 1 is calculated. The number of Lambert fits performed on leg 2 is now reduced because there are fewer options to begin leg 2. Similarly, once the incoming V_∞ from leg 1 and the outgoing V_∞ from leg 2 are available to calculate the ΔV at encounter 2, the legs that do not provide low ΔV at encounter 2 may also be eliminated. The elimination of transfers on leg 2 also removes body/time combinations at encounter 3, thereby reducing the number of Lambert fits for leg 3 as demonstrated in Figure 1.

Once the pertinent trajectory data (most notably the ΔV at encounters) has been calculated, adjoining trajectory segments are matched to produce end-to-end trajectories. For example the calculation of the flyby ΔV at encounter 2 creates a trajectory segment from encounter 1 to encounter 3; similarly, the flyby ΔV at encounter 3 provides the means of connecting encounter 2 to encounter 4. Then all of the encounter 1–3 segments that share the same leg 2 (in Figure 1) as the encounter 2–4 segments are simply matched at leg 2 to create entire encounter 1–4 trajectories. When all of the possible combinations are collected there are usually multiple members represented per trajectory family. For example there could be several trajectories that launch on different dates in August 2020, flyby Jupiter in February 2022, flyby Saturn in February 2024, and arrive on various dates in the winter of 2032. In this case only the trajectory with the lowest ΔV and the trajectory with the lowest flight time are kept for optimization with the assumption that all of the other similar trajectories would converge to the same answer.

For the specific case of the TSSM study we search launch dates between 2018 and 2022 with 15-day step sizes and flight time to Saturn between 5 to 9 years in 60-day step sizes. The bodies allowed to be used for gravity assist to Saturn are Venus, Earth, and Mars. Jupiter is no longer feasible after 2016. In addition, we place constraints on the flight time the trajectory is in the inner solar system and on the flight time between gravity-assist bodies. See Table 1 for a detailed list of parameters used in the initial broad search. Searches were made for up to 4 gravity-assist bodies.

Table 2 shows the number of potential and feasible sequences for 2, 3, and 4 gravity assist flyby bodies to Saturn. The number of potential sequences includes all of the permutations of body/time combinations at each encounter and gives an indication of the size of the search space. This number is primarily driven by the time increment at encounters, the range of dates examined, and the number of bodies available for gravity assist. The number of feasible trajectories is the subset of the search space that satisfies all of the ΔV, V_∞, and flight time constraints specified in Table 1. In the data set of feasible trajectories to Saturn not all are unique transfers, many of the solutions have similar flyby sequences with similar dates. When the trajectories are converted to low-thrust transfers and optimized, the similar trajectories may converge to the same solution. Thus, steps are taken to find the unique solutions by removing trajectories with the same flyby sequences and dates that are a few weeks apart.

Representative broad search results are given in Figure 2-Figure 4, where the total mission ΔV (launch + flyby +arrival) indicates the relative performance of the unoptimized sequences. These trajectories contain maneuvers only at the flybys and the flyby dates do not provide optimal gravity assists, and thus their relative performance does not necessarily correspond to the relative performance of the optimal trajectories. It is assumed that the broad search trajectories with large ΔV are unlikely to result in good optimized trajectories; however, average trajectories from the broad search are often the top performing optimal trajectories, while the best broad search sequences typically end up in the middle of the pack after optimization. Thus the results from the broad search are filtered as little as possible (while keeping the optimization step manageable) to increase the chance of discovering unexpected trajectories with exceptional performance.

Table 1. Parameters for the Initial Broad Search.

Parameter	**Range (step size)**
Launch Date	2018-2022 (15 days)
Maximum Flight Time	9 yrs (60 days)
Flight Time within Inner Solar System	Up to 5 yrs
Flight Time Between Gravity-Assist Bodies	Up to 3 yrs (15 days)
Number of Gravity-Assist Bodies	2,3, and 4
Gravity-Assist Body	Venus, Earth, or Mars (Jupiter require earlier launchs)
Minimum Flyby Altitude	500 km
Maximum Launch V_∞	6 km/s
Maximum Arrival V_∞	9 km/s
Maximum ΔV at Flyby	3 km/s

Table 2. Performance on the Initial Broad Search.

No. of Flybys	No. of Potential Sequences	No. of Feasible Sequences	Unique Sequences
2	4.20 E+09	14,000	861
3	1.96 E+12	170,367	3,379
4	1.34 E+15	46,647	1,168

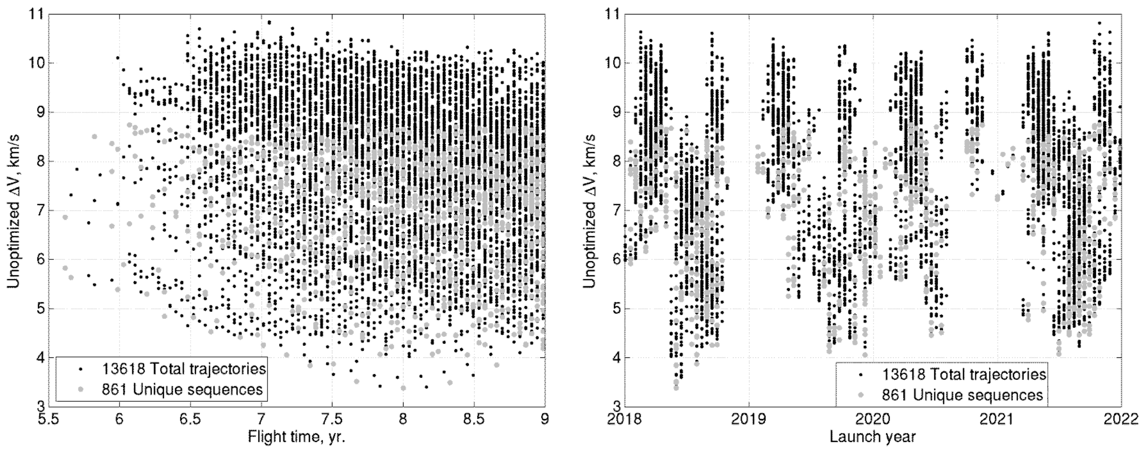

Figure 2. Results of broad search for trajectories with two flybys.

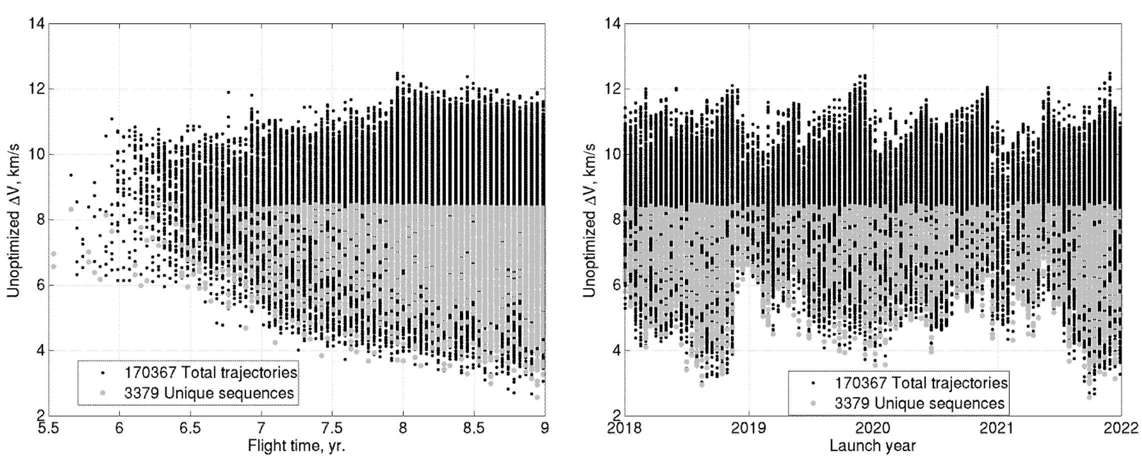

Figure 3. Results of broad search for trajectories with three flybys.

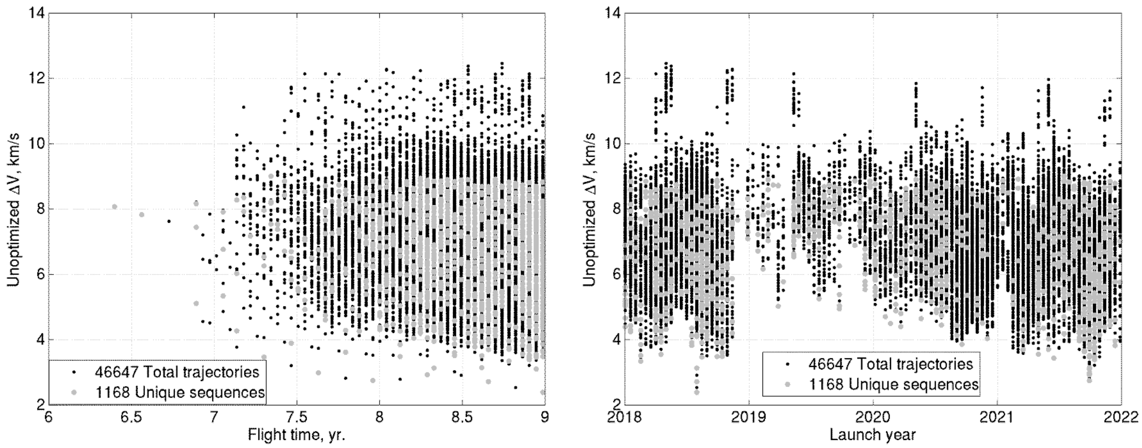

Figure 4. Results of broad search for trajectories with four flybys.

BATCH SEP OPTIMIZATION

The initial broad searches generate thousands of potential trajectories that are then optimized for final mass in a low-thrust trajectory optimization tool called MALTO (Mission Analysis Low Thrust Optimizer)[5]. This process distributes the velocity discontinuities at the flybys to low-thrust arcs throughout the transfers. The trajectory model in MALTO divides each body-body leg into segments where thrusting on a segment is modeled by an impulse at the midpoint of the segment with conic arcs between the impulses. Each individual trajectory can take up to 1 minute to complete. To reduce the optimization time supercomputers were used.

Prior to optimizing the trajectories, an additional 1-year Earth-to-Earth transfer leg is added in the beginning of the 3-flyby sequence; thus, an Earth-Venus-Earth-Earth-Saturn (EVEES) transfer would be inputted into MALTO as an Earth-Earth-Venus-Earth-Earth-Saturn (EEVEES) transfer. Although this set of transfers have 4 flybys it will be described in this paper as the 3-flyby sequence, since the initial search for the transfer is based on the 3-flyby search. The additional Earth-to-Earth leg uses V_∞ leveraging to reduce the launch energy and, thus, increase the launch mass for a fixed launch vehicle[6]. This approach reduces the launch C_3 to be less than 1.0 km^2/s^2 for a majority of the converged results. The 1-year Earth-to-Earth leg was not added to the 4-flyby sequences because this will exceed the 9 years flight time requirement.

The selection of the SEP system adds another dimension to the search space where engine types, number of engines, and power level can be traded. An initial study was done comparing different SEP systems for the TSSM study, which will not be discussed in this paper, but a summary of alternative SEP configuration for the baseline TSSM mission will be presented later. Here we assume up to 2 operating NEXT engines at 15 kW power and a SEP stage dry mass of 778 kg. The optimization parameters used in MALTO are listed in Table 3. We assume a 5% power margin and a 92% engine duty cycle as recommend by Oh et al. for deep space SEP missions[7].

Results for the 2, 3, and 4 flyby cases for the system described above are given in Figure 5-Figure 7. All data points represent converged mass optimal trajectories to Saturn. Final arrival masses at Saturn are plotted as a function of flight time and launch year. Final arrival mass is defined as the mass of the TSSM excluding the Xenon SEP propellant. For the 2 and 3 flyby cases analyses were done to compare the effect of reducing the flight time to Saturn from 9 years down to 7.5 years, which is noted in Figure 5Figure 6. Looking at the top performing cases for the 2 flyby cases, we note about a 200 kg improvement in delivered mass by increasing the flight time from 8 years to 8.5 years and again going from 8.5 years to 9 years (Figure 5). For the 3 flyby cases (Figure 6), we see about a 250 kg improvement in the delivered mass going from 8 to 8.5 years flight time and about a 300 kg improvement comparing 8.5 years and 9 years flight time. Two data points with high delivered mass and a 7.5 year flight time stands out, unfortunately they are July 2017 launches (EEVVES). The results plotted in Figure 7 are for the 4 flyby cases; the results include trajectories with an initial Earth-to-Earth leg and some may be equivalent to those in Figure 6. This approach adds redundancy to the search and optimization method.

Table 3. SEP Optimization Design Parameters.

Parameter	Range
Launch Date	2018-2022
Maximum Flight Time	9 yrs
EP Engine	2 NEXT
Solar Array Power	15 kW
Maximum Arrival V_∞	7 km/s
Minimum Flyby Altitude	300 km
Initial Force Coast Checkout	60 days

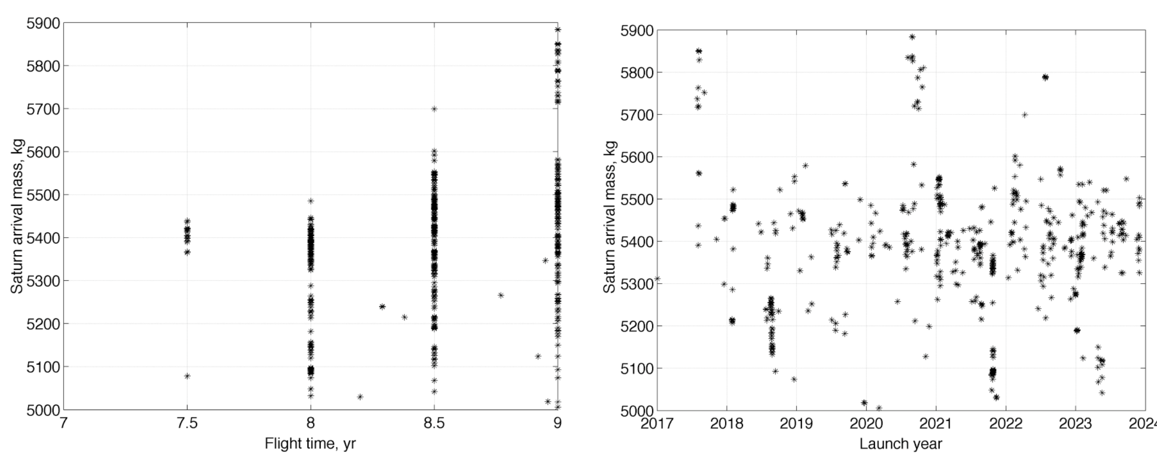

Figure 5. Results of SEP optimization for trajectories with two flybys.

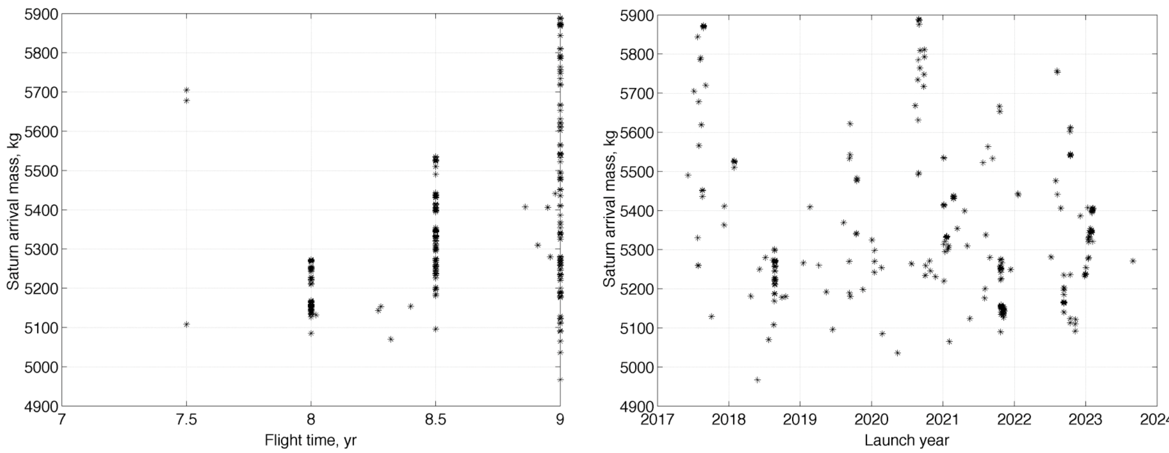

Figure 6. Results of SEP optimization for trajectories with four flybys with the first leg being Earth-to-Earth.

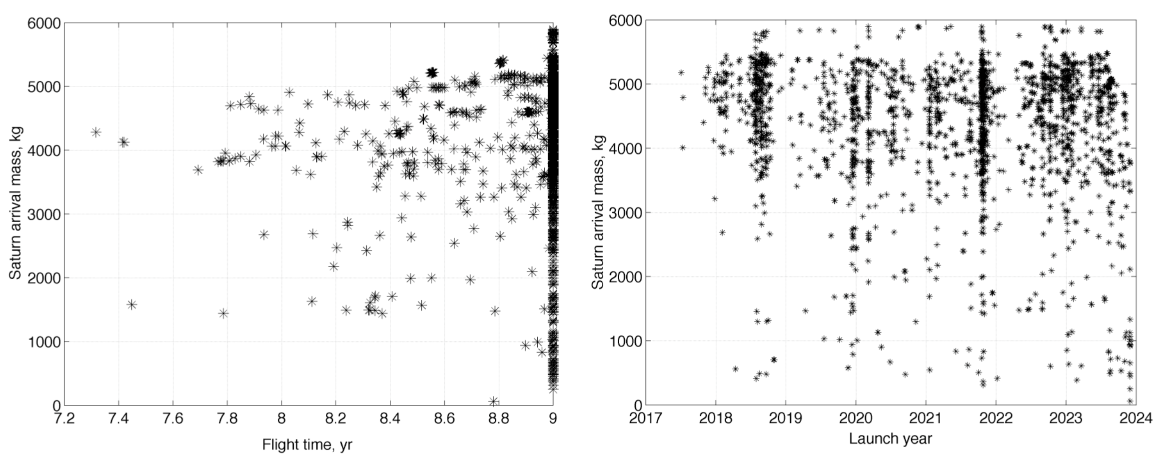

Figure 7. Results of SEP optimization for trajectories with four flybys.

From the figures we can see that transfers to Saturn with high delivered mass exist for a wide range of launch dates and flight time. Only trajectories delivering about 5700 kg (mass of the SEP stage + wet mass of the orbiter + *in situ* payloads) are feasible for the TSSM. From the figures, this requires a flight time of at least 9 years.

Table 4 lists the top mass performing trajectories organized by the number of flyby bodies and then by launch years. Table 5 lists the top performing unique solutions with delivered masses over 5700 kg. Note that the two dominating high performing paths are EEVVES and EEVEES. Representative plots for the two trajectory paths are plotted in Figure 8 and Figure 9 for EEVVES and EEVEES, respectively. From our broad search and optimization we have identified the following sequences that produce high Saturn arrival masses: EEES, EEVVES, EEVEES, EEMMES, EVVEES, EVVMES, and EVEVES, all of which have arrival masses greater than 5300 kg.

The large solution space adds substantial robustness across many potential risks. These trajectories provide the ability to dial-in a flight time for a wide range of masses. This offers an unprecedented and exciting degree of flexibility and robustness for an outer planets mission.

Table 4. Selected Trajectories with Large Saturn Arrival Masses for a Range of Launch Years.

Trajectory Sequence	Launch Date	Time of Flight, years	Arrival V_∞	Arrival Mass, kg
2 Flyby results				
EEES	07-AUG-2017	9.00	7.00	5851
EEES	21-DEC-2018	9.00	6.41	5553
EEES	16-FEB-2019	8.50	6.87	5579
EEES	29-AUG-2020	9.00	6.82	5884
EEES	17-JAN-2021	8.50	7.00	5552
EEES	27-JUL-2022	9.00	7.00	5790
EEES	24-SEP-2023	9.00	6.64	5548
3 Flyby results + Initial E-E leg				
EEVVES	25-AUG-2017	9.00	7.00	5873
EEVVES	29-JAN-2018	8.50	6.97	5528
EEVVES	14-SEP-2019	9.00	6.89	5622
EEVVES	30-AUG-2020	9.00	6.92	5889
EEMMES	17-OCT-2021	9.00	6.63	5666
EEVVES	08-AUG-2022	9.00	7.00	5757
EEVVES	15-OCT-2023	9.00	6.71	5895
4 Flyby results (trajectories w/out an E-E leg)				
EVVMES	08-NOV-2017	9.00	6.57	5364
EVVMES	01-FEB-2018	9.00	6.30	5462
EVEVES	08-SEP-2019	9.00	6.79	5441
EVVEES	27-DEC-2020	9.00	6.31	5314
EVVMES	20-OCT-2021	9.00	6.64	5479
EVEVES	13-OCT-2022	9.00	6.75	5579
EVEVES	30-JAN-2023	9.00	6.43	5379

Table 5. Unique Top Performing Trajectories Organized by Arrival Mass

Trajectory Sequence	Launch Date	Time of Flight, years	Arrival V_∞	Arrival Mass, kg
EEVVES	15-OCT-2023	9.00	6.71	5895
EEVVES	30-AUG-2020	9.00	6.92	5889
EEVEES	15-OCT-2023	9.00	6.56	5842
EEVEES	29-AUG-2020	9.00	6.82	5833
EEVVES	11-AUG-2022	9.00	7.0	5737

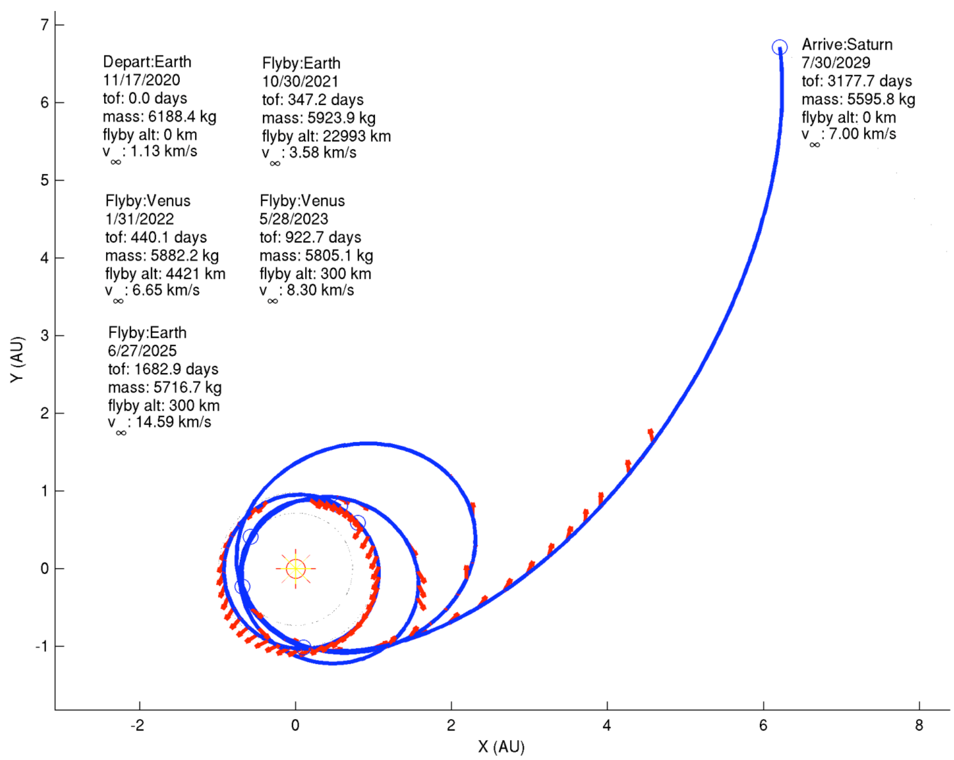

Figure 8. Representative EEVVES trajectory where the red arrows are location of thrusting.

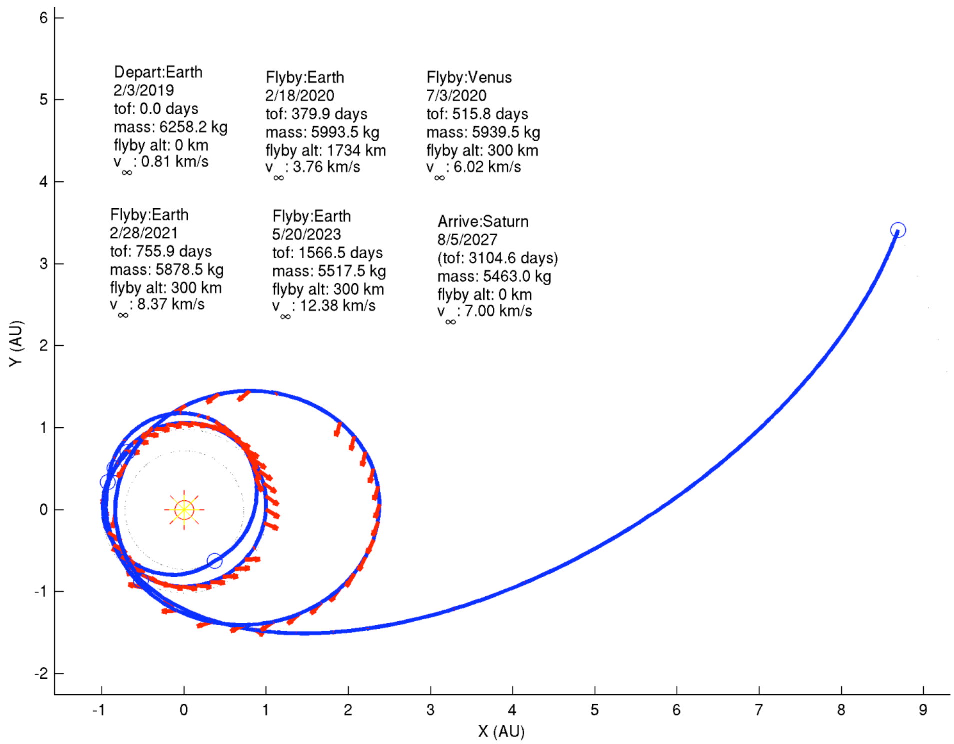

Figure 9. Representative EEVEES trajectory where the red arrows are location of thrusting.

TSSM INTERPLANETARY BASELINE

The broad optimization search identified 2 potential flyby sequences that can be used for the TSSM baseline, EEVVES and EEVEES. After refining the search to maximize orbiter mass instead of arrival mass at Saturn, which reduced the arrival V_∞ at Saturn down to 6.6 km/s which reduces SOI, the EEVEES transfer was selected as the baseline trajectory.

Figure 10 shows the SEP trajectory selected for the TSSM. Table 6 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 (for planetary protection). The next 3.3 years is a ballistic cruise with no flybys or SEP thrusting. For a detailed description on the TSSM concept please see Strange et al[8].

The TSSM baseline design currently uses 2 NEXT ion engines. In addition, alternate trajectory options were found that use lower performance BPT-4000 Hall thrusters or XIPS ion engines that deliver the full Baseline Flight System mass for only a slightly longer flight-time (Table 7). Table 8 list trajectory solutions for alternative launch years from 2018 to 2022, including the 2020 baseline. Consecutive launch years are achievable by adding an additional Earth flyby and/or extending the flight time, with the exception of the APR-2022 launch which has about a 2 month shorter flight time than the baseline for the same flyby sequence.

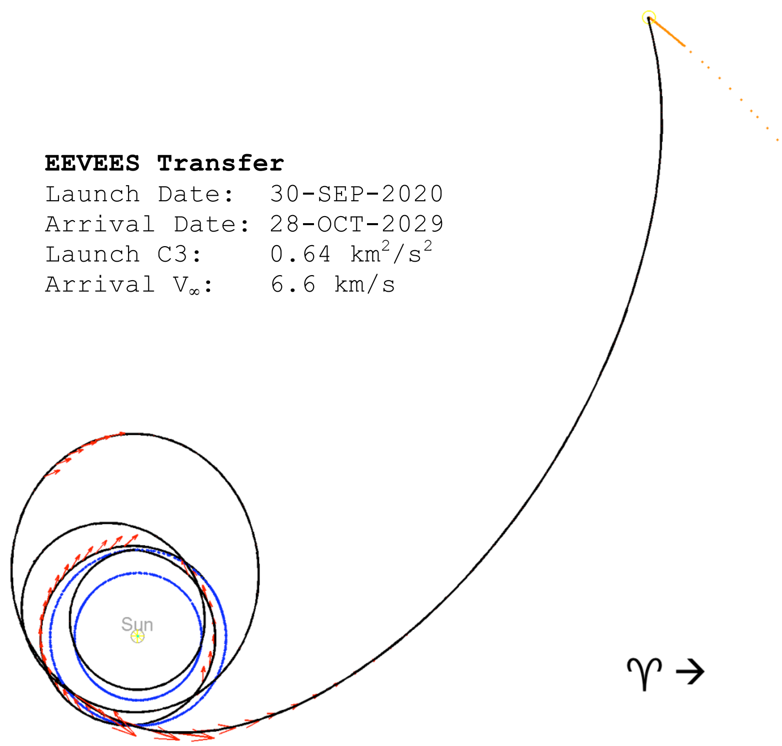

Figure 10. Baseline 2020 TSSM interplanetary trajectory where the arrows are location of thrusting.

Table 6. Interplanetary Events for the TSSM

Event	Date / Altitude
Launch	10-30 SEP-2020
Start SEP Thrusting	01-DEC-2020
Earth Flyby 1	27-OCT-2021 / 16,900 km
Venus Flyby	04-FEB-20233 / 5,300 km
Earth Flyby 2	11-JUN-2023 / 4,500 km
Earth Flyby 3	11-JUN-2025 / 600 km
End SEP Thrusting	14-OCT-2025
SOI	28-OCT-2029

Table 7. Comparison of Alternative SEP Configuration for a September 2020 Launch

Engine	No. Engines	Array Power, kW	Time of Flight, years	Saturn Arrival Mass, kg
XIPS	4	15	9.4	5718
XIPS	3	10	10.3	5621
BPT-4000	4	15	9.3	5735
BPT-4000	3	10	9.4	5584

Table 8. Alternative SEP Trajectories for Other Launch Years

Launch Year	Trajectory Sequence	Launch Date	Time of Flight, years	Saturn Arrival V_∞, km/s	SOI ΔV, m/s	Saturn Arrival Mass, kg
2018	EEEVEES	JUL-2018	9.5	6.20	680	5700
2019	EEVEES	JAN-2019	9.0	6.20	680	5700
2020	EEVEES	SEP-2020	9.0	6.66	745	5795
2021	EEEVEES	OCT-2021	9.4	6.10	670	5675
2022	EEVEES	APR-2022	8.8	6.10	670	5675

CONCLUSION

A thorough and systematic search for transfers to Saturn using SEP with multiple gravity assist flybys has successfully found dozens of high mass performing trajectories applicable to the Titan Saturn System Mission. This method will enable a variety of missions to the outer planets for all mission classes. We have found trajectories for a wide range of launch dates and flight times and the added flexibility that SEP provides, in trading flight time and mass, creates an almost continuum in the solution space.

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NOTATION

SEP Solar Electric Propulsion

TOF Time-of-Flight

TSSM Titan Saturn System Mission

ΔV Magnitude of a change in velocity, km/s

V_∞ Excess velocity at infinity

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