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Titan Aerogravity Assist for Saturn Orbital Insertion and Study of Enceladus

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A combination of trajectory analysis software, atmospheric entry analysis software, and original scripts was used to design a mission from Earth to the Saturn system. This mission was aided by an aerogravity assist at Saturn's moon Titan among other maneuvers. The final orbit in the Saturn system was chosen based on its feasibility leaving Titan's atmosphere and proximity to Enceladus to facilitate study of Saturn's highly scientifically interesting moon. The trajectory from Earth to the Saturn system was carried out in Mission Analysis Environment (MAnE), the aerogravity assist through Titan's atmosphere was calculated in the Program to Optimize Simulated Trajectories (POST), and the resulting orbit through the Saturn system was created using Python scripts created by the group. A final trajectory was found that utilized multiple gravity assists to reduce the fuel load and an aerogravity assist through Titan to successfully enter into the desired science orbit around Saturn.

I. Nomenclature

AGA	=	aerogravity assist
C_D	=	drag coefficient
C_L	=	lift coefficient
C_3	=	characteristic energy
EES	=	Earth-Earth gravity assist ending at Saturn
EEJS	=	Earth-Earth-Jupiter gravity assist ending at Saturn
EJS	=	Earth-Jupiter gravity assist ending at Saturn
FPA	=	flight path angle
kg	=	kilogram
km	=	kilometer
MAnE	=	Mission Analysis Environment
m	=	meter
NASA	=	National Aeronautics and Space Administration
POST	=	Program to Optimize Simulated Trajectories
r_p	=	radius of perigee
s	=	second
$v_{E,Titan}$	=	entry velocity with respect to Titan
v_∞	=	velocity at infinity
Δv	=	change in velocity (resulting from a maneuver)
θ	=	intercept location

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II. Introduction

Recent observations of the Saturn system have generated great interest in the moon Enceladus. Water geysers have been identified in the southern hemisphere and have been found to contain organic compounds [1]. These observations strongly support the need for a return to the Saturn system specifically designed to evaluate Enceladus in greater detail. The goal of this study is to design an interplanetary trajectory to the Saturn system which utilizes an aerogravity assist (AGA) at Titan to alter the spacecraft's velocity, resulting in an orbit about Saturn which will allow for frequent flybys of Enceladus for scientific observation.

In previous papers authored by our group, the use of an AGA maneuver at Titan for orbital capture about Saturn was evaluated for a Cassini-class vehicle [2]. These studies confirmed that the proposed maneuver is a viable alternative to the use of a traditional propulsive orbital insertion maneuver to change the magnitude and direction of the inbound v_∞ vector (Figure 1). Candidate mission plans were previously developed based on overall performance including total Δv, flight duration, launch year, and launch energy [3]. Once promising mission opportunities had been identified, the candidate trajectories were evaluated for their arrival conditions at Titan.

The Saturn arrival declination and v_∞ were used to find the probe's velocity relative to Titan ($v_{E,Titan}$) at an altitude of 1000 km, corresponding to the Titan atmospheric interface. As in previous papers, our coordinate system is defined such that the probe arrives from the negative y-direction as Titan orbits posigrade about Saturn at the origin; the Titan-spacecraft intercept position in the Saturn-centered reference frame is designated by the angle θ in Figure 1. In the current paper, we build upon this concept and discuss mission opportunities for future return voyages to the Saturn system, as well as expand our solution into three-dimensional space.

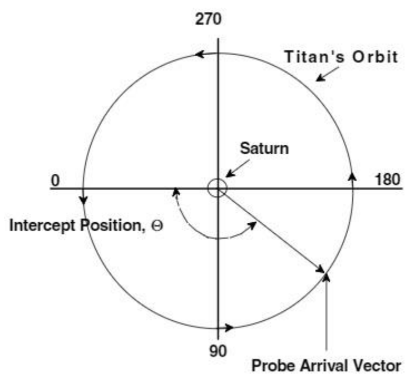

Figure 1: Coordinate system used for Titan arrival geometry.

To obtain the trajectory to the Saturn system from Earth the software, Mission Analysis Environment (MAnE) [4] was used to generate several different trajectories. These were compiled and optimized to select the trajectory with the best overall parameters for the mission. Various mission opportunities were examined using MAnE to determine the desired range of intercept positions that would provide Titan atmospheric entry velocities of 6 to 10 km/s. This velocity range was chosen to avoid the excessive aerothermal environment that would be associated with higher entry speeds. The approach trajectories for each candidate mission opportunity were then compared to Titan ephemeris data, and the Saturn system arrival dates were adjusted to accurately target the optimal Titan intercept positions.

Using these final trajectories, the AGA maneuvers were computed using the Program to Optimize Simulated Trajectories (POST) [5]. POST was used to incrementally view the projected trajectory for the spacecraft based on the input parameters of C_L, C_D, entry FPA, azimuth, velocity, mass, and bank angle. A multitude of trajectories were analyzed, differing all every variable, in order to narrow down the optimal conditions for a successful orbital insertion maneuver. Utilizing Titan's atmosphere in this way allows us to achieve a larger turn angle and Δv_∞ without the use of an impulsive maneuver as illustrated in Figure 2. The AGA maneuvers were then compared to the necessary outbound conditions which would result in a suitable orbit about Saturn.

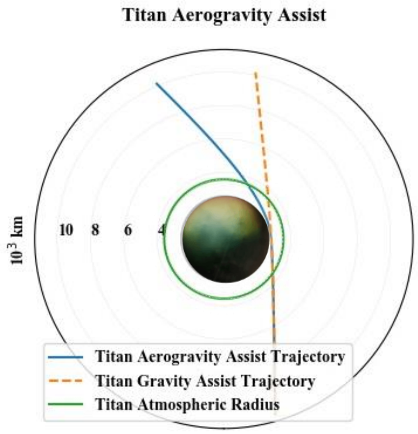

Figure 2: Effect of AGA on trajectory through Titan's atmosphere.

The required outbound conditions in two-dimensions were determined based on the maximum and minimum allowable velocities for each flight path angle. The maximum velocity results in an orbit with a perigee radius equal to the orbital radius of Enceladus, allowing for a single rendezvous opportunity. The minimum velocity is the velocity required to prevent the spacecraft from crashing into Saturn and allows for two potential crossings of Enceladus' orbit. The flight path angle is measured clockwise from the local horizontal. For the three-dimensional case, each combination of flight path angle and inclination will have one solution, corresponding to the velocity resulting in an orbit whose descending node has a radius equal to Enceladus' orbital distance.

III. Methodology and Assumptions

A. MAnE

The first step of this mission was to approach the Saturn system with an effective, optimized trajectory. To do this, three types of trajectories were investigated. An Earth-Jupiter gravity assist (EJS), an Earth-Earth gravity assist (EES), and an Earth-Earth gravity assist to a Jupiter gravity assist (EEJS). The flybys of Earth in the EES were powered while all other flybys for other cases were unpowered. Potential dates for these trajectories were gathered from NASA's Trajectory browser from the NASA AMES Research Center [7]. These dates were then entered into MAnE for further investigation. MAnE's trajectory calculation program was run to optimize the trajectory. MAnE calculated the important dates, information on pass distances, and the Δv values for the trajectory. It also provided the arrival excess speed (v_∞) and declination with respect to Saturn upon arrival to be used for calculating the AGA at Titan. This process was repeated for each trajectory over a number of different launch dates, and the results were tabulated and graphed.

B. POST

The goal for the Titan AGA was to slow the spacecraft down enough that the resultant velocity would allow for orbital insertion into the Saturn system. A spacecraft with aerodynamic characteristics similar to the Apollo entry vehicle was used for the simulations. In order to gain an accurate understanding of the effect of Titan's atmosphere on the entry vehicle, a thorough table for density values had to be obtained. The Yelle density model [9] was used to map the density values for all altitudes. This model assumes that the atmosphere of Titan began at an altitude of about 1000 km. A variety of trajectories were plotted to better understand the effect of the initial conditions on the spacecraft's trajectory through Titan's atmosphere. Trajectories with the entry vehicle's lift vector pointing downwards towards Titan's center (180º bank angle) were a focal point of the POST analysis. Few trajectories were analyzed with the lift vector pointed perpendicular to Titan's center (90º bank angle). The mass of the vehicle was varied from 50 kg to 600 kg, to determine a suitable payload mass that would allow for a successful maneuver. Entry FPAs were also optimized to increase the time the spacecraft spent in the atmosphere in order to maximize the reduction in speed without crashing into Titan.

The simulation began 49,000 km out from Titan's surface, so even a small change in the entry flight path angle could be the difference between the spacecraft crashing and a successful maneuver. The arrival conditions of the spacecraft were obtained through the MAnE analysis. From this the declination was entered into the simulations using the initial azimuth variable in POST, 90+|declination| for arrival from the west and -90+|declination| for arrivals from the east. The inbound velocity at 49,000 km was entered into POST and an appropriate flight path angle guessed. The simulation was then run and the FPA adjusted based on the need for more or less deceleration. Once the desired initial and final conditions were obtained, the initial longitude was adjusted such that the velocity components were entirely in the +y and -z directions. With this accounted for, the turn angle could be determined.

C. Saturn System Scripts

Scripts written in the Python language were used to determine the family of outbound velocity vectors from Titan which allowed for insertion into orbit around Saturn. As an initial step, the family of suitable orbits was found in two dimensions before solving the full three-dimensional problem. At each FPA from 0º to 359º the maximum velocity, the value which results in an orbit where r_p is equal to Enceladus's orbital radius, was calculated along with the minimum velocity, the lowest value of velocity before the spacecraft would be pulled into Saturn. For the 3D case, orbital parameters resulting from each combination of flight path angle and inclination were calculated and possibilities iterated through until an orbit was achieved which equaled that of Enceladus's. The velocities at each flight path angle were sorted to find those which have a r_p less than or equal to that of Enceladus's radius, velocity less than Saturn's escape velocity, and r_p greater than Saturn's radius. Scripts were also created to convert the output of MAnE into a form usable in POST.

IV. Results and Discussion

D. MAnE

The cases investigated for this mission were spread over a large range of dates. Overall, the EJS, while having the most direct trajectory, had the highest C_3 values at around 76 to 120 km^2/s^2 and closest pass distances with Jupiter such as 1.83 J-radii. This brings in the concern of intense radiation that the craft could suffer on the way to Saturn. The EES had some major improvements on these values, with C_3 values around 30 km^2/s^2 and had no concern of passing Jupiter. However, the best results were obtained from an EEJS trajectory with launch dates starting in 2036, the full data for which can be found in Table 1 in the Appendix. Figure 3 and Figure 4 contain the important data for the trajectories from the 2036 launch dates.

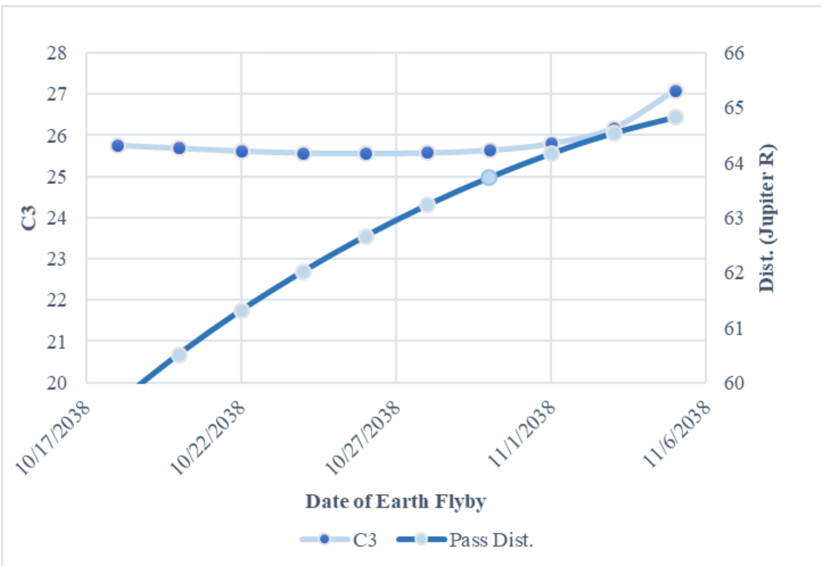

Figure 3: C_3 and Jupiter pass distance vs. Earth flyby date for 2036 launch.

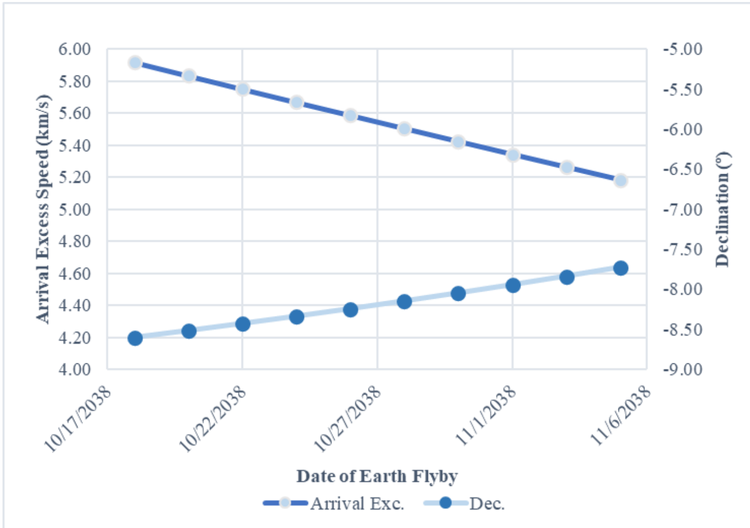

Figure 4: Arrival excess speed and declination vs. Earth flyby date for 2036 launch.

As seen in Figure 3 and Figure 4, the lowest C3 value for this trajectory is 25.569 km^2/s^2. The trajectory has an average transit time of 6.72 years and some of the lowest total Δv values obtained. Furthermore, the pass distance to Jupiter is sufficiently far enough from Jupiter to not be concerned about intense radiation. A possible downside to the space-burn with an EES is an increased fuel consumption required to achieve this. This is lessened with significantly smaller C_3 values as seen in Table 1, but it should be noted. The projection of this trajectory's path around Earth and Jupiter can be seen in Figure 5.

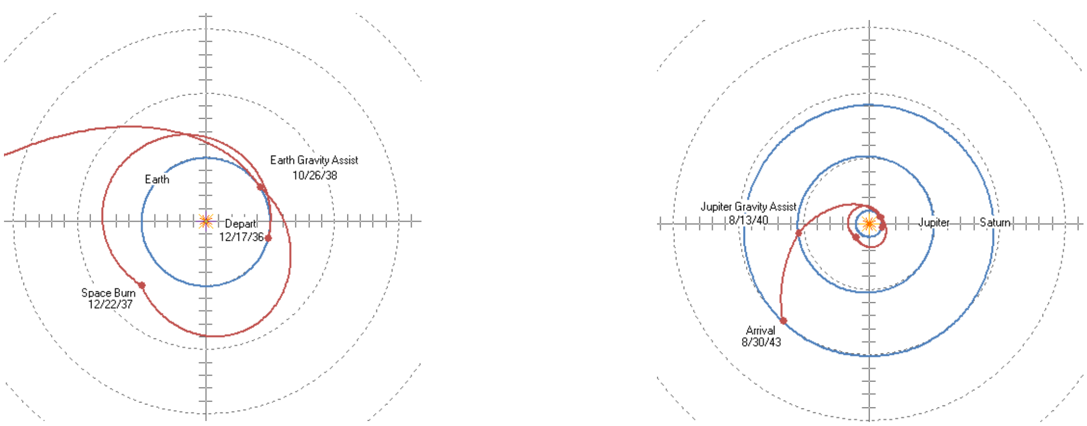

Figure 5: Final Earth-Saturn trajectory.

E. POST

Figure 6 shows that the arrival flight path angle at 1000 km will have a pretty drastic change in the turn angle and deceleration of the spacecraft. This means that coming in at an accurate angle is important because as shown even a few hundredths of a degree can be the difference between a 40º and a 10º turn angle. On average, the 50 kg mass saw the most drastic difference in turn angle through the range of entry flight path angles as all the other weights were more concentrated along the bottom of the 'L' shape. For example, the 50 kg mass sees a difference of roughly 30º in turn angle over a range of roughly 1 degree of flight path angle while the 100 kg mass only sees a difference of roughly 14º. The 100 kg mass also has more points along the shallower part of the curve whereas the 50 kg mass is pretty well distributed along the sharp peak. Overall, the 600 kg mass saw the least effect of entry flight path angle, only experiencing a difference of 3º in turn angle for a range of 0.7º of entry flight path angle.

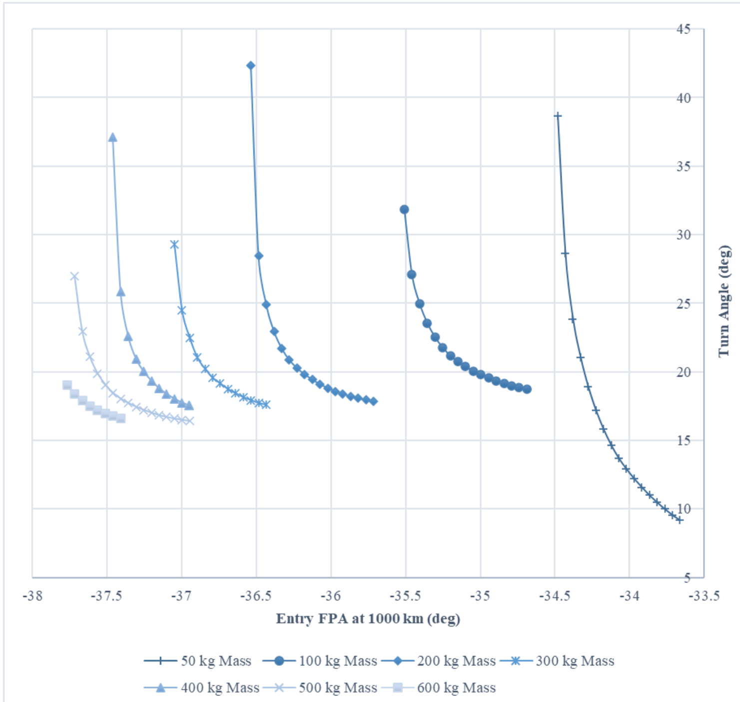

Figure 6: Effect of spacecraft mass and entry FPA on turn angle for 12 km/s entry velocity and 180º bank angle.

Figure 7 shows how a 90º bank angle affects the trajectory of the spacecraft. Two cases are plotted, one for a 100 kg and 300 kg spacecraft. The 90º bank angle shows very little change in turn angle as the spacecraft comes in at a steeper flight path angle. This is because the entry vehicle does not stay in the atmosphere as long as the 180º bank angle case. With every little change in the entry flight path angle, the resulting turn angle will change dramatically.

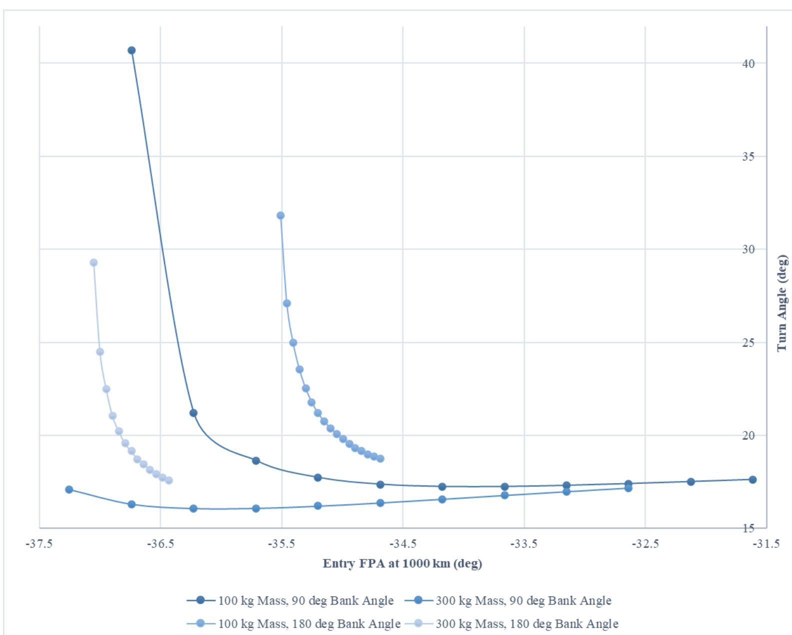

Figure 7: Effect of entry FPA, mass, and bank angle on turn angle for 12 m/s entry velocity.

The final work done on this part of the project was using POST to simulate trajectories at intercept angles between 60º and 140º in increments of 10º. The purpose of this was to find the approximate slowest possible outbound velocities we could achieve before falling into an elliptic orbit around Titan. The results can be found in Table 2 in the Appendix.

It can be observed that the slowest exit velocity achieved was 1761.2 m/s which provided a turn angle of 57.54º. In theory, further tweaking of the flight path angle at the 60º intercept point should provide the largest possible turn angle because it enters Titan's atmosphere with the largest velocity and as such can stay within the atmosphere longer before reaching a velocity that would cause it to crash. The only problem with this is that it would require an FPA that is accurate to four decimal places which leaves very limited margin for error. On average it should be expected for the largest turn angles to be seen between intercept angles of 60º and 90º because the inbound velocity relative to Titan will be higher than its mirrored counterparts from 90º to 140º. This is because the velocity of Titan is opposite the probe resulting in higher relative velocities than when Titan is moving in the same direction.

It is worth noting the table has two entries for a 60º intercept: max and realistic. The difference between these two is the degree of accuracy in the inbound flight path angle. The maximum velocity reduction is found at -86.798º while the realistic case was run at -86.79º. The difference of 0.008º proves to be a tremendous difference at an initial altitude this high above the surface, also noted in the fact that an initial FPA of -86.80º would result in the probe losing too much velocity and crashing into the surface of the moon. The best way to combat this would be to measure the flight path angle at a lower altitude within these runs where variation of FPA will have a reduced effect on deceleration as seen in Figure 7. In this figure we can see that turn angle - which is directly related to deceleration - is changing with relatively manageable increments of 0.1° to the flight path angle when measured from an altitude of 1000 km as opposed to the drastic changes seen in incremental FPA changes of 0.001º at altitudes of 49000 km.

One note is that the results in Table 1 show the greatest reduction in velocity which would be accompanied by the maximum relative heating rates. This means that while POST may mark these velocities as possible in terms of the kinematics, heating analysis done in the future may prove them impossible for the craft to handle.

F. Saturn System Scripts

The family of velocities found in the 2D case can be seen in Figure 8. The magnitude of the velocity resulting from each flight path angle is plotted to show the flight path angles with a wide range of acceptable velocities, no acceptable velocities, and a small window of acceptable velocities. For this case, an acceptable velocity is defined as one which is greater than the velocity at which the spacecraft would crash into Saturn, is less than the velocity for which the spacecraft would have r_p equal to Enceladus's orbital radius, allows for two crossings of Enceladus's orbit, and is less than Saturn's escape velocity. These borders are all noted in order to observe which FPAs result in velocities close to the boundaries or no acceptable velocities. Interesting behavior can be noted around 90º and 270º, where the velocity was close to Saturn's escape velocity or resulted in a r_p similar to that of Saturn's radius.

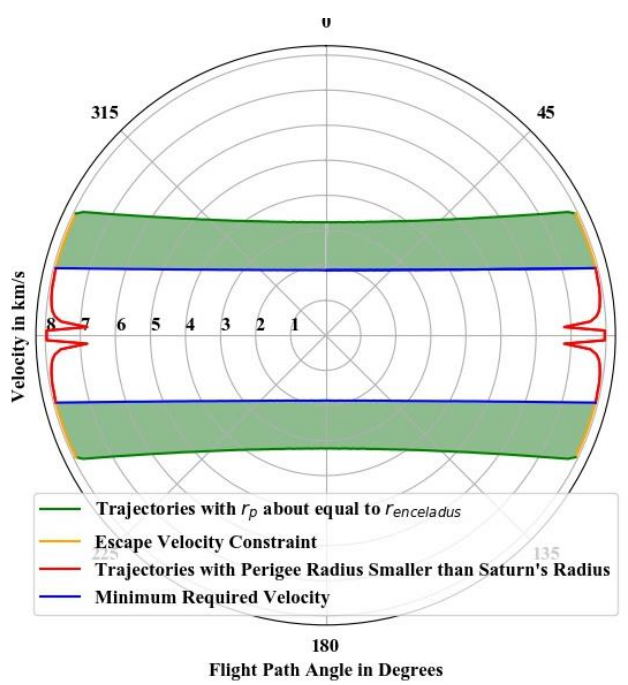

Figure 8: Family of acceptable post-AGA 2D velocity vectors with respect to Saturn.

The family of 3D velocity vectors calculated using the scripts can be seen in Figure 9. Highlighted in green are the velocities that are feasible for this mission.

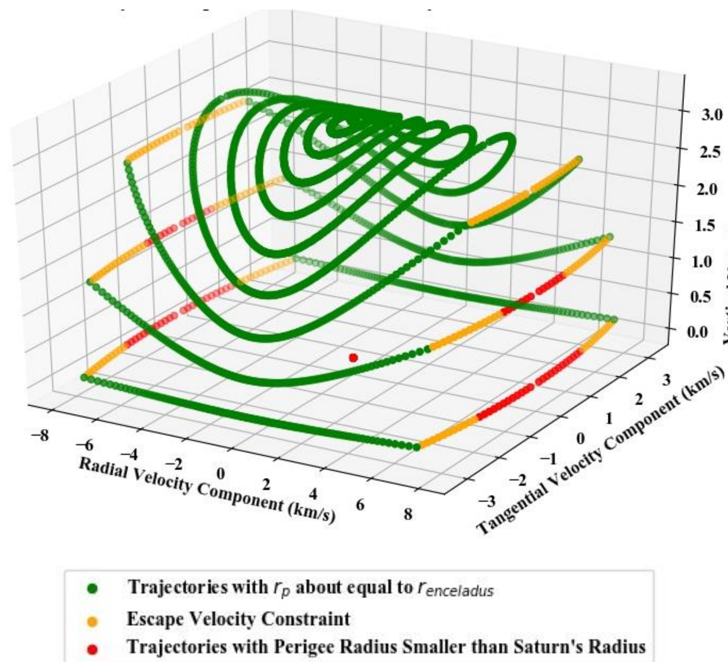

Figure 9: Family of acceptable post-AGA 3D velocity vectors with respect to Saturn.

Once output from POST was obtained, the resulting velocity components were compared to the family of acceptable velocities found in the 3D case. This resulted in a highly elliptical orbit, as seen in Figure 10.

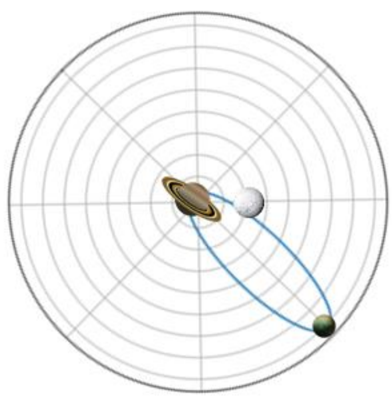

Figure 10: Final science orbit around Saturn.

V. Conclusion

A mission from Earth to the Saturn system in order to enter into an orbit around Saturn that allows for observation of Enceladus was designed. Using the software Mission Analysis Environment, the trajectory from Earth was optimized, resulting in a departure date in 2036, a trajectory that utilized both an Earth gravity assist and a Jupiter assist, and a transit time of 6.7 years. Given this trajectory, the Program to Optimize Simulated Trajectories was used to design an aerogravity assist through Titan's atmosphere which slowed the spacecraft's speed the most without causing extensive heating damage to the spacecraft. Finally, scripts were created which calculated all possible orbits exiting Titan and compared those to the previous output to find an orbit with those entry conditions and allowed for frequent observation of Enceladus.

Overall, the trajectories best optimized for the given mission included multiple gravity assists. This had the advantage of significantly reducing the launch C_3 values thereby reducing launch costs. The only drawback to this system is a slightly increased transit time. The results from POST show that it is possible to achieve substantial deceleration through Titan's atmosphere and provide the groundwork for possible starting points to achieve a final solution set that results in a stable orbit around Saturn. On average the minimum velocities for a 600kg spacecraft to maintain its hyperbolic trajectory through Titan's atmosphere are around 1700-2000m/s. Slower velocities in the craft being caught in an elliptic orbit around Titan and at some point the slower velocities result in the untimely end of our probe upon Titan's surface. This means that any Titan-reference exit velocity necessary for capture into orbit around Saturn of over 1700m/s will be possible to achieve as long as there is sufficient heat shielding to withstand the radiative and conductive heating the probe would undergo. From the Saturn system scripts, the family of acceptable velocities was calculated and relationships between MAnE, POST, and this family obtained.

In the future more cases can be investigated. Perhaps trajectories that focus on using other planets for a gravity assist can further reduce the C3 needed for the mission. Venus or Mars could provide an important steppingstone in the overall trajectory. POST input decks to complete this project were saved and can be passed on to future groups to continue this work. Trajectories can continue to be optimized to figure out the optimal payload mass, bank angle, and entry flight path angle to result in a sufficient turn angle and still slow down enough to be able to capture into orbit around Saturn. Peak heating and acceleration loads need to be analyzed to ensure a successful mission. A few models have been developed to describe Titan's atmosphere and can help calculate convective and radiative heating effects. The Saturn system scripts relied on the assumption of a two-body problem, and to expand upon this, calculations could be done estimating the gravitational effects of Saturn, Titan, and the spacecraft. Currently, the spacecraft is assumed to only be affected by Saturn's gravity as soon as it leaves Titan's atmosphere, so fixing this assumption by accounting for the gravity of both while the spacecraft is near Titan could make an impact on the results.

Appendix

Table 1: Possible Earth-Earth-Jupiter Gravity Assist Trajectories 2036.

Launch Date	Space Burn Date	Earth Flyby Date	Jupiter Flyby Date	Arrival Date	Transit Time (days)	C_3 (km^2/s^2)	Arrival Excess Speed (km/s)	Pass Distance (J-Radii)	Declination (º)	Δv (m/s)	Space Burn (m/s)
12/11/2036	1/10/2038	10/18/2038	8/5/2040	7/2/2043	2393.868	25.769	5.9177	59.63	-8.6020	5131	790
12/12/2036	1/6/2038	10/20/2038	8/7/2040	7/16/2043	2406.977	25.697	5.8330	60.52	-8.5164	5091	753
12/14/2036	1/2/2038	10/22/2038	8/9/2040	7/31/2043	2419.931	25.631	5.7496	61.32	-8.4286	5063	728
12/16/2036	12/28/2037	10/24/2038	8/11/2040	8/15/2043	2432.957	25.582	5.6671	62.03	-8.3382	5046	713
12/17/2036	12/22/2037	10/26/2038	8/13/2040	8/30/2043	2446.779	25.569	5.5853	62.67	-8.2450	5041	709
12/21/2036	12/15/2037	10/28/2038	8/15/2040	9/14/2043	2458.413	25.586	5.5039	63.24	-8.1487	5042	709
12/23/2036	12/8/2037	10/30/2038	8/17/2040	9/30/2043	2471.947	25.646	5.4229	63.74	-8.0491	5047	712
12/25/2036	11/29/2037	11/1/2038	8/19/2040	10/16/2043	2485.527	25.813	5.3422	64.18	-7.9461	5061	719
12/27/2036	11/20/2037	11/3/2038	8/21/2040	11/1/2043	2499.720	26.184	5.2621	64.55	-7.8395	5102	744
12/29/2036	11/10/2037	11/5/2038	8/23/2040	11/18/2043	2515.061	27.098	5.1824	64.84	-7.7292	5214	819

Table 2: Possible trajectories through Titan's atmosphere with an initial altitude of 49000 km at varying intercept angles

Intercept Angle (º)	Initial Longitude (º)	Initial Azimuth (º)	Initial FPA (º)	Initial v_∞ (m/s)	Final v_∞ (m/s)	Turn Angle (º)
60 (max)	-86.842	100.35	-86.798	13372	2054.5	54.39
60 (realistic)	-86.842	100.35	-86.79	13372	6404.8	26.07
70	-86.845	100.87	-86.79	12757	4144.5	28.19
80	-86.845	101.53	-86.78	12041	5022.4	21.94
90	-86.845	102.35	-86.77	11255	4787.1	22.27
100	-93.15	-76.631	-86.762	10411	1761.2	57.54
110	-93.15	-75.349	-86.744	9520.1	2747.6	48.59
120	-93.15	-73.735	-86.72	8601.3	2036.2	48.87

130	-93.15	-71.699	-86.685	7676.7	2710.3	36.05
140	-93.15	-69.148	-86.638	6778	2778.9	33.93

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