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Engineering Notes

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Enceladus Mission Architecture Using Titan Aerogravity Assist for Orbital Capture About Saturn

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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 possible organic compounds [1]. These observations strongly support a return to the Saturn system specifically designed to evaluate Enceladus in greater detail and perhaps to return a sample from the geyser's plume.

We previously described an aerogravity assist (AGA) maneuver, in which Titan's atmosphere and gravitational field are used to decelerate a spacecraft and deflect its trajectory, resulting in a closed orbit about Saturn [2]. A similar concept using wave-rider configurations was described by Randolph and McRonald [3,4] and evaluated using an analytical approach. In contrast, we have numerically simulated AGA trajectories for low and medium lift-to-drag (L/D) vehicles. In this paper, we describe Titan AGA maneuvers in greater depth, and evaluate their potential for orbital capture of a Cassini-class vehicle. The targeted Saturn orbit has a periapsis near the radius of Enceladus's orbit, allowing repeated close passes. This orbit can be achieved by directing the outbound hyperbolic excess speed (V_∞) with respect to Titan nearly opposite in direction to Titan's orbital velocity, resulting in a final apoapsis near Titan's orbital radius. Depending on the interplanetary trajectory and the exact Titan encounter location, the proposed maneuver would provide a velocity increment (ΔV) in excess of 6 km/s.

Titan has a near-circular, equatorial orbit about Saturn at a radius from the planetary center of 1.22×10^6 km. Its orbital velocity (V_T) and period are ~5.58 km/s and 15.95 Earth days, respectively. Titan's orbit lies well outside the ring system, which extends in the equatorial plane to a radius of approximately 480,000 km. Enceladus orbits in nearly the same plane, at a radius of 238,000 km and with an orbital period of 32.9 h.

The mission concept is illustrated in Fig. 1, where the upper diagram shows Titan's velocity vector and that of the probe before and after the AGA maneuver, and the lower panel illustrates the range of potential directions for the outbound V_∞, any of which will produce a periapsis at Enceladus's orbital radius. To achieve this desired periapsis, the probe's velocity immediately after completion of the Titan AGA should have a magnitude 3.18 km/s with respect to (WRT) Saturn and a flight path angle of 0 deg. The various possible directions for this velocity vector (Fig. 1b) determine the inclination of the final orbit about Saturn. Some variation in the velocity after the AGA from this target value may be acceptable (or even desirable) and would yield a periapsis slightly inside or outside Enceladus's orbital radius. In addition, the vehicle may have a radial velocity component WRT Saturn after the maneuver, resulting in an apoapsis outside Titan's orbital radius. For simplicity, the latter scenario is not considered in this preliminary study.

Titan is particularly well suited for an AGA maneuver because of its relatively weak gravitational field, coupled with its unique atmospheric structure. Although Titan's radius is only 2575 km, atmospheric pressure at ground level is approximately 1.6 times that on Earth, and the atmosphere extends to an altitude of approximately 1000 km (compared with approximately 125 km for Earth). These factors combine to yield relatively low atmospheric flight velocities at a given density level for a planetary entry probe, especially when compared with a vehicle entering Saturn's atmosphere. This makes a Titan AGA maneuver preferable to direct aerocapture using Saturn's atmosphere because of the much lower entry speed and the lower aerodynamic heating. The less-severe heating translates directly into weight savings in the vehicle's thermal protection system (TPS).

Methodology

In this study, we assume an inbound V_∞ of 5.393 km/s with respect to the Saturn system. At the node, the spacecraft's trajectory has an angle with respect to Saturn's ring plane of 16.43 deg, and the vehicle arrives from below. (These values were chosen to be similar to those of the Cassini mission). Two aeroshells designs are examined, one a blunt body with a lift-to-drag ratio of 0.48, and the other a triconic with an L/D of 1.0. The triconic configuration is similar to one previously evaluated for use on human Mars missions [5]. Transitional and free-molecular aerodynamics are not considered. A reference area of 19.6 m^2 is assumed; this value was selected to fit the aeroshell within the 5-m-diam launch shroud of a Titan IV, the vehicle used to launch Cassini. The probe mass used for orbital insertion in all simulations is 3400 kg, which includes the weight of the aeroshell. Again, this was chosen to be similar to the mass propulsively inserted into orbit during the Cassini mission.

Trajectory simulations are conducted using the three-dimensional version of the program to optimize simulated trajectories (POST) [6]. The trajectory optimization feature of POST is not employed. Nominal atmospheric density profiles for Titan are taken from Yelle et al. [7]. Titan encounter trajectories are calculated beginning at a radius of approximately 40,000 km, comparable to the radius of Titan's sphere of influence. Atmospheric entry velocities are specified at 1000 km above Titan's surface. The outbound velocity vector of the probe is added to Titan's orbital velocity to determine the final orbit about Saturn. For simplicity, we have assumed that Titan has a circular orbit; because the orbital eccentricity is actually 0.028, this assumption should introduce little error. We have chosen a coordinate system in which Titan's orbit lies in the X–Y plane, and a projection onto this plane of the probe's velocity vector at the beginning of the Titan encounter establishes the positive Y direction

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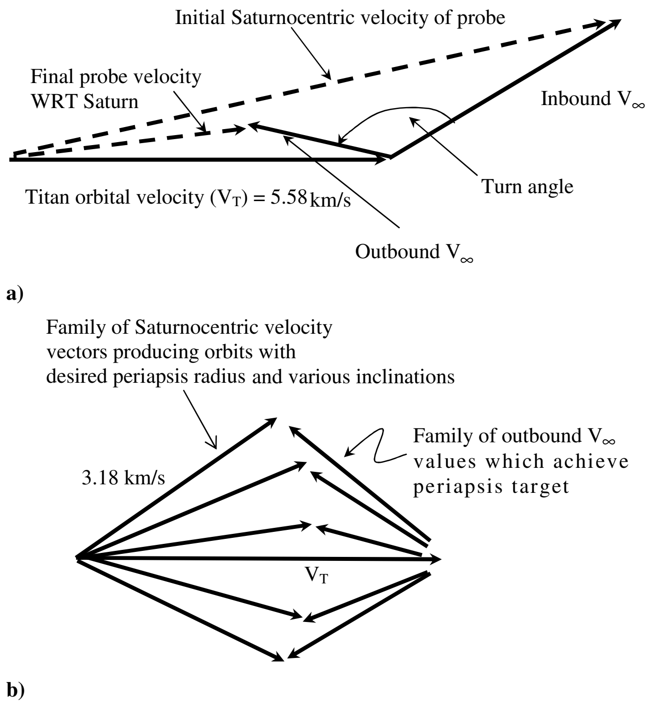

Fig. 1 a) A vectorial diagram of Titan's velocity and the probe's velocity before and after the AGA maneuver. b) Probe velocity diagram following the AGA capture maneuver. The magnitude of V_∞ has been reduced by atmospheric drag.

(Fig. 2a). The location of the probe's encounter with Titan in this coordinate system is given by the angle Θ as illustrated in Fig. 2a.

Results

The vehicle's atmospheric entry speed depends strongly upon where in Titan's orbit the encounter occurs, with values ranging from approximately 5 to 15 km/s (Fig. 2b). Velocities over 10 km/s are excluded due to the severity of the aerothermal environment. This constrains the Titan encounter to occur at positions between about 106 and 254 deg. A Titan intercept at a position near 180 deg minimizes the atmospheric entry speed and optimizes the aerothermal environment; however, previous work has shown that aerodynamic entry corridors (the range of potential entry angles that can result in a successful capture) increase in width as entry velocity increases [2]. Moreover, Fig. 3 shows that the achievable periapsis radius of the final Saturn orbit grows larger than the targeted value of 238,000 km as the Titan encounter shifts from 110 toward 180 deg. This is due to the aeroshell's inability to execute the increasingly large turn required to direct the outbound velocity in the direction opposite Titan's orbital motion (Fig. 4 and 5). The appropriate direction for the outbound velocity vector is necessary to lower the periapse as much as possible and bring the orbit in close proximity to Enceladus's orbit. Figure 5 also illustrates that as the atmospheric exit speed from Titan decreases, the maximum achievable turn angle during the AGA maneuver increases. This results from the fact that a lower exit speed corresponds to a larger energy dissipation during the maneuver, a longer duration atmospheric pass, and more opportunity for the AGA maneuver to influence the trajectory. An outbound V_∞ of about 2.4 km/s, directed opposite to Titan's orbital velocity, will yield a final orbit for the probe with its periapse at Enceladus's orbital distance from Saturn and the apoapse at Titan's orbital distance.

It should be noted that Figs. 3 and 5 have been calculated assuming that the vehicle's lift vector is directed toward Titan's surface throughout the trajectory, corresponding to an overshoot trajectory. This strategy provides the maximum achievable turn angle. Because the inbound approach vector and Titan's orbital velocity vector are nearly in the same plane (because the two vectors nearly intersect at the encounter location), proper selection of the *B*-plane geometry will yield an outbound V_∞ approximately in the desired direction without requiring an orbital plane change (in the Titan-centered reference frame). Therefore, as executed in this study, the maneuver occurs in a single plane in the Titan-centered reference frame but produces a plane change in the Saturn-centered frame.

Three major factors must be examined to determine the optimal Titan encounter location: aerodynamic corridor width, entry velocity/aerothermal heating, and the achievable Saturn periapsis radius. Because these three factors do not reach their optimal states at a common location, a compromise intercept location must be found that satisfies the requirements for each. Figure 3 indicates that the triconic aeroshell ($L/D = 1.0$) is able to achieve values close to the targeted periapsis radius for Titan intercept positions between 115 and 128 deg, corresponding to atmospheric entry speeds of 9.2 to 8.0 km/s. Although it is unable to reach the target periapsis for the range of encounter locations considered here (115–135 deg), it appears that for a Titan intercept between 105 and 110 deg, the blunt body may be able to provide a satisfactory final Saturn orbit, with a periapsis radius near the desired value; the atmospheric entry speeds at Titan corresponding to these encounter locations range from 10.0 to 9.6 km/s. Corridor widths for both probes have previously been shown to be satisfactory for the ranges of entry speeds required to reach the target orbit [2].

Although the lower entry speeds allowed by its high L/D make the triconic seem preferable to the blunt configuration, the larger area requiring thermal protection materials may offset the speed advantage. Determining which of these vehicles is preferable will require a detailed evaluation of the structural and TPS requirements for each design.

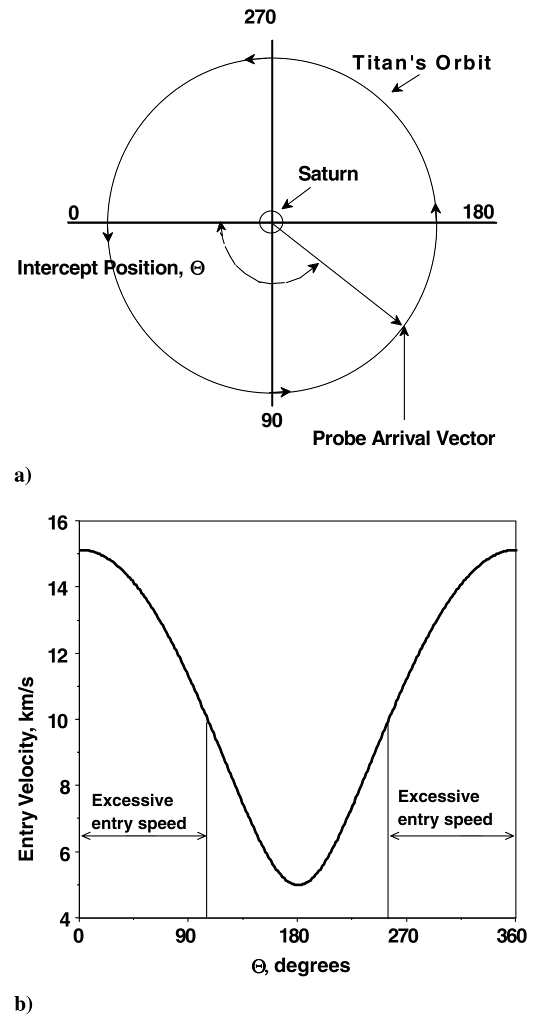

Fig. 2 a) Coordinate system for Saturn/Titan encounter. b) Variation of atmospheric entry speed at Titan with encounter location Θ.

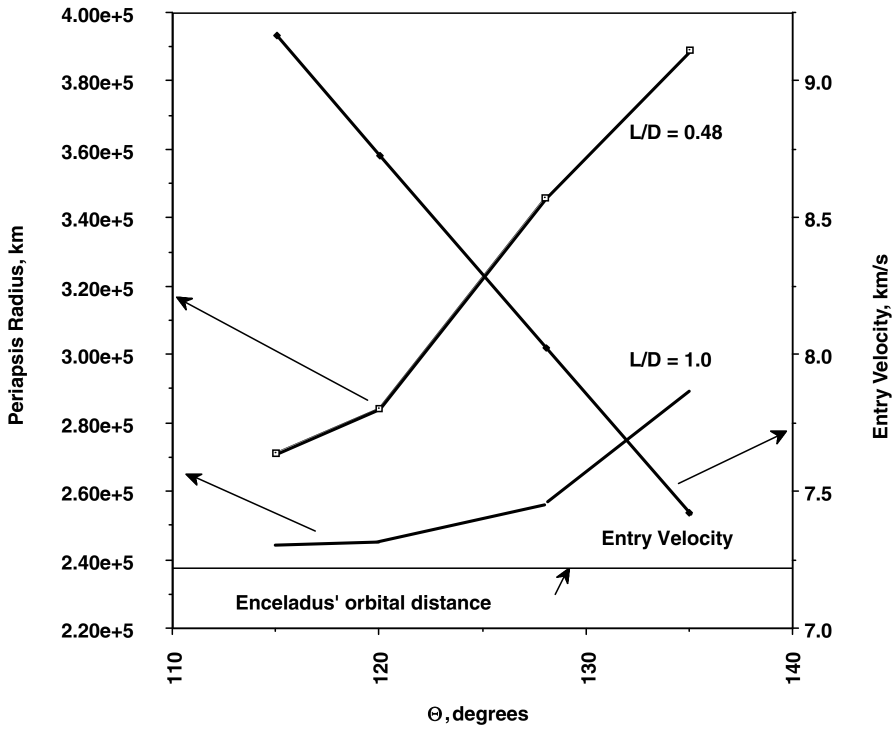

Fig. 3 Titan atmospheric entry speed and achievable Saturn periapse radius vs Titan intercept position Θ for a full lift-down trajectory.

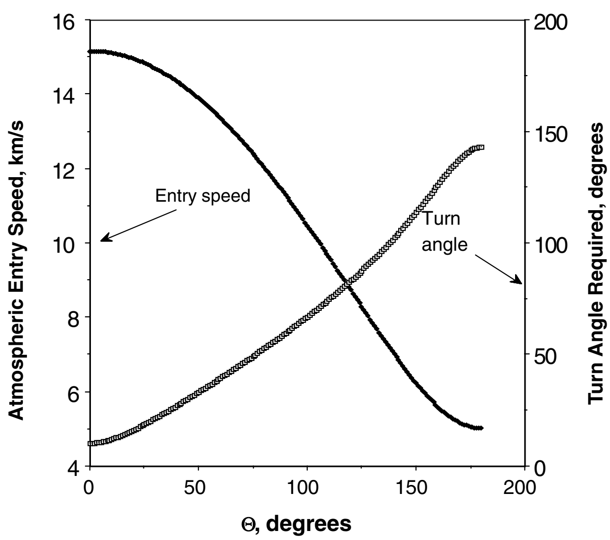

Fig. 4 Atmospheric entry speed and turn angle required to achieve minimum periapse radius vs Titan intercept position.

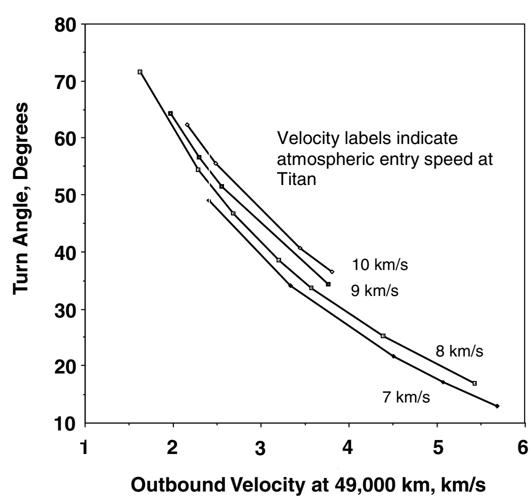

Fig. 5 Maximum turn angle achievable for $L/D = 0.48$, full lift-down trajectory.

To achieve an outbound V_∞ in the desired orbital plane, the spacecraft should pass to the side of Titan during the AGA, not over the poles. For an encounter in quadrant 2 (between 90 and 180 deg as defined in Fig. 2), a pass to the right side of Titan allows the outbound V_∞ to offset Titan's orbital velocity more effectively, and the vehicle is more likely to realize its desired periapsis radius. Encounters in quadrant 3 (between 180 and 270 deg) will have similar results, but during the AGA, the vehicle should pass to the left of Titan, as seen during approach, to achieve the proper alignment of the outbound V_∞ and Titan's orbital velocity. A pass over Titan's polar regions directs the outbound V_∞ out of Titan's orbital plane, leading to a more highly inclined final orbit about Saturn with a larger periapsis radius. If circumstances cause the probe's initial Saturn orbit after the AGA maneuver not to be at the desired inclination, subsequent Titan flybys could be used to adjust the inclination or other orbital parameters.

Conclusions

A triconic aeroshell with an L/D of 1.0 appears to be capable of performing a Titan aerogravity assist, resulting in the capture a 3400 kg Cassini-class spacecraft into an Enceladus crossing orbit. Atmospheric entry velocity for this triconic probe at Titan will be between 8 and 9 km/s. A blunt aeroshell with an L/D of 0.48 may also be able to accomplish the maneuver, but would require higher entry speeds, resulting in a more severe aerothermal environment. The fact that a triconic vehicle can accomplish the maneuver makes the use of a Titan AGA, a promising means of orbital capture at Saturn.

Future work should be done to determine the impact of variation in vehicle mass on the AGA maneuver; specifically, would a blunt body aeroshell be able to accomplish the required turn at lower atmospheric entry speeds if a lower mass were assumed for the probe? Specific mission opportunities should be identified and the maneuver evaluated for the corresponding arrival vectors. An updated Titan atmospheric model must be employed in future work, making use of data gathered by Huygens. Although the impact of atmospheric dispersions on entry corridor width has been described previously, the ability of a guidance and control scheme to target both outbound energy and direction under multiple off-nominal conditions must be evaluated using a Monte Carlo approach.

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