An Investigation of Aerogravity Assist at Titan and Triton for Capture into Orbit About Saturn and Neptune

2nd International Planetary Probe Workshop
August 2004, USA

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ABSTRACT

Previous work by our group has shown that an aerogravity assist maneuver at the moon Titan could be used to capture a spacecraft into a closed orbit about Saturn if a nominal atmospheric profile at Titan is assumed. The present study extends that work and examines the impact of atmospheric dispersions, variations in the final target orbit and low density aerodynamics on the aerocapture maneuver. Accounting for atmospheric dispersions substantially reduces the entry corridor width for a blunt configuration with a lift-to-drag ratio of 0.25. Moreover, the choice of the outbound hyperbolic excess speed (with respect to Titan) strongly influences the corridor width. Given the influence of these two parameters, certain mission scenarios may be feasible using a blunt aeroshell, while other mission designs would likely require a biconic vehicle with a higher lift-to-drag ratio. Preliminary simulations indicate that the same technique may be feasible for capture into orbit about Neptune using the tenuous atmosphere of Triton.

1. INTRODUCTION

Aerocapture and aerogravity assist maneuvers have long been recognized as methods by which otherwise impractical interplanetary missions could be accomplished. Our group recently proposed that an aerogravity assist maneuver at the moon Titan could be used to capture a probe into orbit about Saturn, using an aeroshell with a with a low to moderate lift-to-drag ratio (0.25 to 1.0).[1] This approach provides for capture into orbit about the gas giant, while avoiding the very high entry speeds and aerothermal heating environment inherent to a trajectory thru the atmosphere of Saturn itself.

Titan is unique among moons in the solar system in that it has an atmosphere considerably thicker than Earth's, with a ground level density of about 5.44 kg/m^3. Moreover, its atmosphere extends much higher above the surface than Earth's atmosphere, with the density at 800 km above the surface being approximately the same as that on Earth at 132 km.

Titan has a near-circular, equatorial orbit about Saturn at a radius from the planetary center of 1.22 (10^6) km and an orbital velocity of approximately 5.57 km/s. This orbit is well outside the ring system, which extends in the equatorial plane to a radius of approximately 480,000 km. A wide range of target orbits about Saturn can be achieved by means of a Titan aerogravity assist maneuver. The final orbit will depend on both the orientation and the magnitude of the outbound hyperbolic excess speed with respect to Titan after the AGA maneuver.

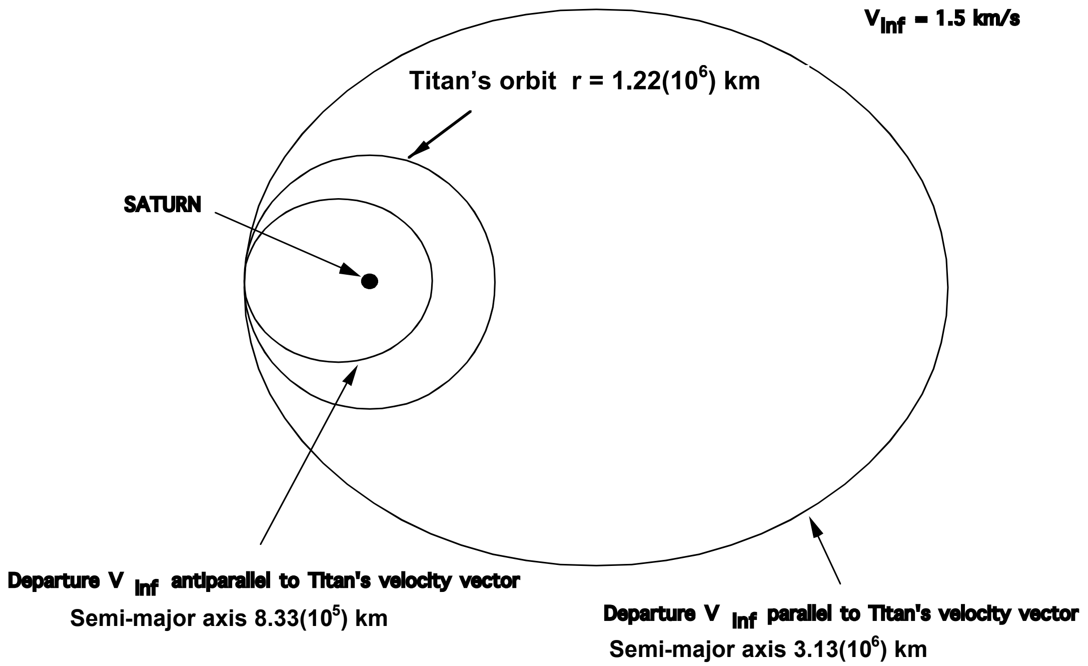

Figure 1. Potential variation in Final Saturn Orbit for an Outbound V_{inf} of 1.5 km/s

By lining up the outbound V_{inf} with Titan's orbital velocity vector, an orbit can be reached with a periapsis radius equal to that of Titan's orbit and a higher apoapsis. If the outbound V_{inf} is in the opposite direction, the final orbit will have an apoapsis radius equal to that of Titan's orbit and a lower periapsis radius (Fig. 1). An orbital periapsis of approximately 160,000 km would allow the probe to pass through the gap between rings F and G, a maneuver which the Cassini spacecraft recently accomplished without any apparent damage. Achieving this periapsis radius would require an outbound V_{inf} of approximately 2.89 km/s, opposite in direction to Titan's orbital velocity vector. However, since Titan's orbit lies virtually in the same plane as Saturn's rings, any mission using this strategy will be complicated by the need not to fly through the debris field. If Titan's orbital velocity vector and the outbound V_{inf} are co-linear, the final spacecraft trajectory about Saturn would lie very near or in the ring plane. Directing an outbound V_{inf} of 3 km/s 15 degrees above the ring plane would result in a final orbit about Saturn with its apoapsis coincident with its ascending node at Titan's orbital distance, its periapsis coincident with the descending node and in the Cassini division (between rings F and G), and an orbital inclination of approximately 16 degrees (Fig. 2 and 3).

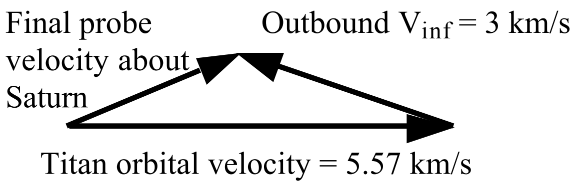

Figure 2. Velocity vector diagram for insertion into inclined orbit about Saturn

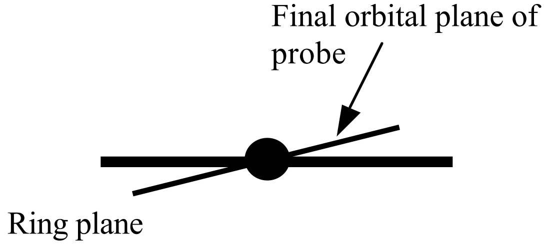

Figure 3. Edge view of possible final orbital geometry

2. METHODOLOGY

The atmospheric entry corridor of an aerocapture maneuver is bounded by the overshoot and undershoot limits. These represent the shallowest and steepest angles at which the spacecraft can enter the atmosphere and successfully complete a capture into the desired orbit. The width of the corridor depends on many factors, including the entry velocity, the atmospheric density profile, the vehicle's lift-to-drag ratio and limits which may be imposed on the vehicle's deceleration or aerodynamic heating. For this study, trajectory simulations were run using the three-dimensional version of POST.[2] No constraints were placed on the vehicle's deceleration or aerothermal heating. All simulations were begun at an altitude of 905 km at zero degrees latitude and with a due east azimuth. Entry angles are measured at the 905 km altitude.

Overshoot boundaries were found by directing the vehicle's lift vector toward Titan's surface (a vehicle roll angle of 180 degrees) and adjusting the entry angle until the desired outbound V_{inf} was achieved. Various target values of the outbound V_{inf} were evaluated, corresponding to different final orbits about Saturn. The undershoot boundaries were found by flying a full lift up trajectory and adjusting the entry angle until the target outbound V_{inf} was achieved.

Nominal, minimum and maximum atmospheric density profiles seen in Fig. 4 were based on the work by Yelle.[3] Atmospheric winds were not considered, nor were horizontal density dispersions.

For Titan, four vehicle configurations were evaluated. The first was a blunt aeroshell with an L/D of 0.25 that has been considered by other investigators for use on a conventional Titan aerocapture maneuver.[4] An ellipsled with an L/D of 0.39, an Apollo-derived capsule flying at a high angle of attack (L/D of 0.482), and a biconic with an L/D of 1.0 were also evaluated. (It is recognized that flank heating may prevent an Apollo configuration from flying at such a high alpha, but the configuration was chosen simply as a "place holder" to determine the corridor available to a vehicle with an L/D in this range.) The vehicle mass was assumed to be 600 kg, and a reference area of 12.56 m^2 (corresponding to a base radius of 2 meters) was used for all three blunt configurations. For the biconic, a base radius of 1 m was used, giving a reference area of 3.14 m^2.

3. RESULTS

The corridor width for the capsule with an L/D of 0.25 is shown in Fig. 5 as a function of entry velocity for both the nominal and extreme atmospheric models and for three target values of the outbound V_{inf}. In general, the high density atmosphere produced a shallower undershoot bound than the nominal atmosphere did, and the low density atmosphere produced a steeper overshoot bound than was allowed with the nominal atmospheric profile. Since the density profile which will be encountered is not known prior to entry, it is necessary to consider the corridor width with these narrower limits. The corridor defined in this manner must be wide enough to allow for off-nominal atmospheric entry angles, knowledge errors and uncertainties in the expected aerodynamic performance of the vehicle. Current estimates indicate that insertion angle errors of +/- 0.9 degrees are to be expected.[5] Therefore, a corridor width of 2.0 degrees is the minimum considered acceptable for this study. Improvements in interplanetary navigation capabilities that result in a more precise insertion angle would allow this corridor requirement to be relaxed.

Our original study considered only an outbound V_{inf} of 1.5 km/s in determining the corridor bounds (Ref. 1). From Fig. 5 it is apparent that an increase in the targeted outbound V_{inf} from 1.5 to 3.0 km/s substantially reduces the aerodynamic corridor width. This finding follows the trend seen in conventional aerocapture studies, where corridor widths often decrease as the target apoapse (and orbital energy) increase. This reflects the decreased control the vehicle's aerodynamics can exert over the trajectory as the duration of the atmospheric pass and the required energy loss are reduced.

Thus, if we assume that two degrees of corridor width are required to allow for off-nominal entry angles and aerodynamic dispersions, the choice of entry velocity and outbound V_{inf} will determine whether a given L/D provides a sufficient corridor. If a target orbit about Saturn with a periapsis in the Cassini division is desired, the outbound V_{inf} will need to be near 3 km/s, and a lift-to-drag higher than 0.25 will be required.

Fig. 6 shows corridor widths for all four vehicles, assuming an outbound V_{inf} of 3.0 km/s (this is considered the most likely target value of V_{inf}, since it provides a close approach to Saturn, opportunities for repeated Titan flybys and a close view of the ring system). From this Fig., it is apparent that the Ellipsled (with an L/D of 0.39) can provide a satisfactory corridor only at entry speeds of 9.5 km/s or more. The modified Apollo configuration at an angle of attack of 30 degrees (L/D of 0.482) provides a sufficient corridor width at an entry speed of 8 km/s or higher. As the entry speed decreases, vehicle configurations with higher lift-to-drag ratios (such as a biconic) become necessary unless better targeting of the atmospheric entry angle can be achieved. The arrows in Fig 6 indicate the reduction in corridor width caused by atmospheric uncertainty, with the solid lines representing the nominal atmosphere and the dashed lines showing the results for Yelle's low and high density profiles.

While all the results presented up to this point have assumed continuum aerodynamics, we conducted an evaluation of the impact of free molecular and transitional aerodynamics on vehicle trajectories and corridor bounds. For the vehicles considered here, there was no appreciable difference between results obtained neglecting and accounting for low-density influences on aerodynamic characteristics. We assume this results from the fact that the vehicles' deceleration almost exclusively occurs in the continuum flow regime (Fig. 7)

4. POTENTIAL APPLICATION AT NEPTUNE AND TRITON

NASA has conducted fairly detailed studies in recent years of aerocapture at Neptune;[6,7] an important conclusion of this work has been that the required aeroshell would have a much higher mass fraction than those considered for use at Mars, Earth or Titan, with 50% or more of the total probe mass being devoted to the aeroshell. This situation greatly decreases the appeal of aerocapture for Neptune missions.

Preliminary calculations indicate that the approach discussed in this paper for use at Titan/Saturn may also be feasible for capturing a probe into orbit about Neptune using an aerogravity assist maneuver at the moon Triton. This maneuver would be substantially different from the Titan scenario, in that the atmosphere of Triton is extremely tenuous, with a surface pressure of approximately 16 microbars and a pressure at 48 km altitude of 2 microbars (Fig. 8).[8] Despite the very thin atmosphere, trajectory simulations show that either a blunt aeroshell (L/D = 0.25) or a ballute could be used to accomplish a capture into orbit about Neptune, assuming the vehicle encounters atmospheric conditions similar to those shown in Fig. 8. Figures 9 shows the corridor width for a 600 kg aeroshell (L/D of 0.25, reference area of 12.56 m^2), with the vehicle targeted to an atmospheric exit velocity of 4.8 km/s. As can be seen, the corridor width for this vehicle is unlikely to prove adequate for the maneuver in light of the high degree of temporal variability in Triton's atmospheric density profile, In addition, the vehicle often flies to altitudes less than 10 km above Triton's surface during its atmospheric trajectory. Therefore, we also considered the use of a non-releasing ballute with a reference area of 100 m^2. Without modulation of the release time, variation in the atmospheric entry angle produces alterations in the outbound energy as shown in Fig 10. The ballute has a significant advantage in that it flies at very high altitudes, thereby providing a greater "margin of error" with regard to surface impacts.

4. CONCLUSIONS AND FUTURE WORK

The use of an aerogravity assist maneuver at Titan to capture a vehicle into orbit about Saturn appears to offer the potential for a less severe aerothermal enviroment than a direct capture using Saturn's atmosphere, while allowing for a variety of final orbital geometries. Depending on the choice of final Saturn orbit and the atmospheric entry speed at Titan, blunt aeroshells or vehicles with mid-range lift-to-drag ratios (such as biconics) offer adequate entry corridor width, even when accounting for atmospheric dispersions. Low density aerodynamics seem to have minimal impact on typical trajectories, but the choice of outbound V_{inf} strongly influences entry corridors.

Future studies of the topic must address optimal approach geometries, aerodynaic heating during the Titan atmospheric trajectory, thermal protection system requirements and TPS mass fractions. Guidance algorithms must be developed that can target both the magnitude and direction of the outbound hyperbolic excess speed in order to achieve the desired orbit about Saturn. In addition, the use of ballutes for capture at both the Titan/Saturn and

Neptune/Triton systems should be further examined.

5. REFERENCES

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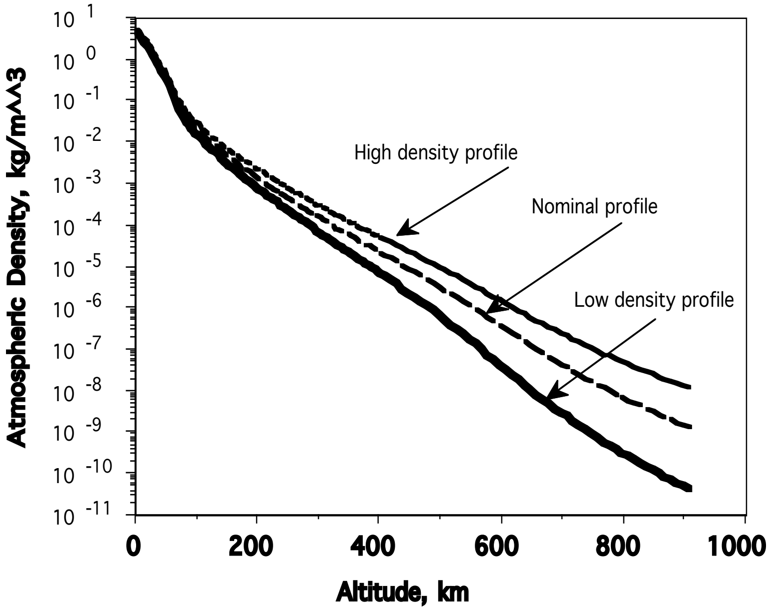

Figure 4. Titan atmospheric density profiles from Yelle (Ref. 4)

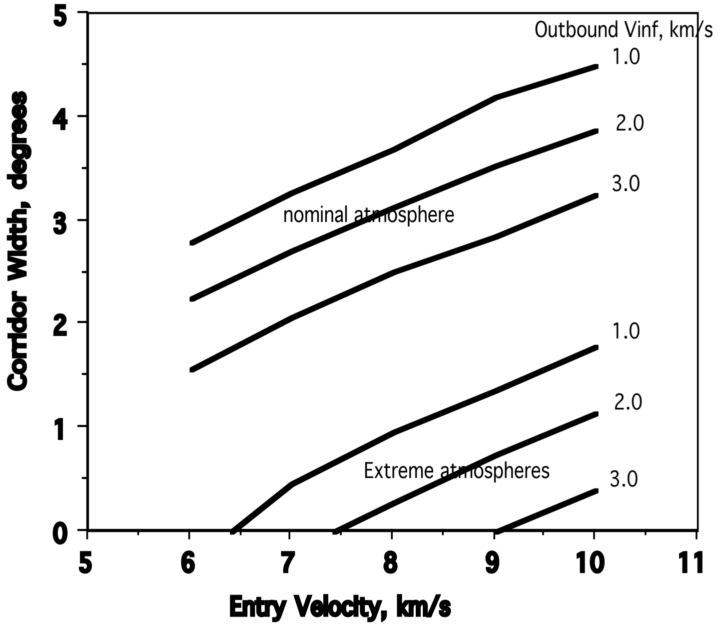

Figure 5. Corridor width at Titan vs entry velocity for a probe with an L/D of 0.25

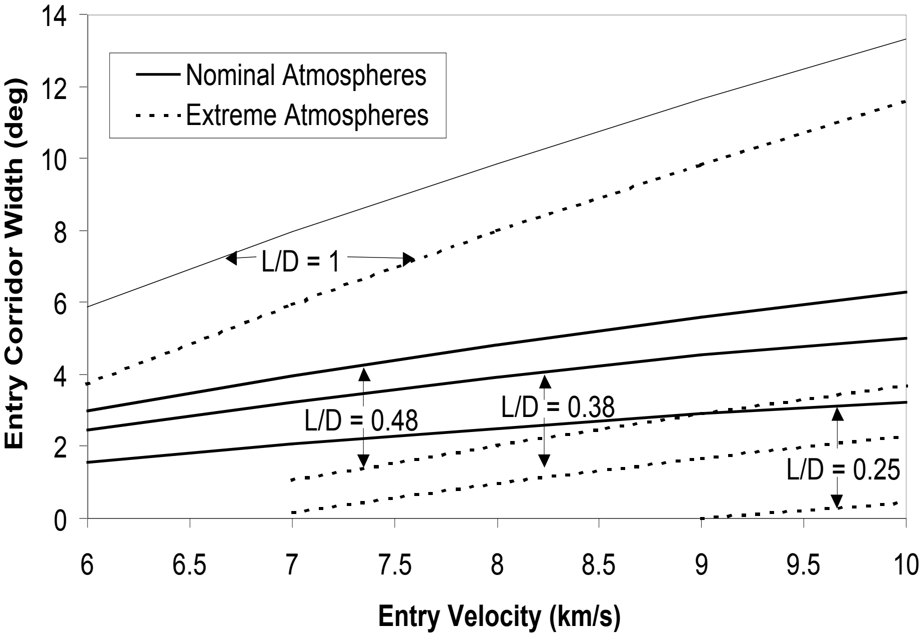

Figure 6 Titan/Saturn AGA maneuver corridor width vs. entry angle for various vehicles

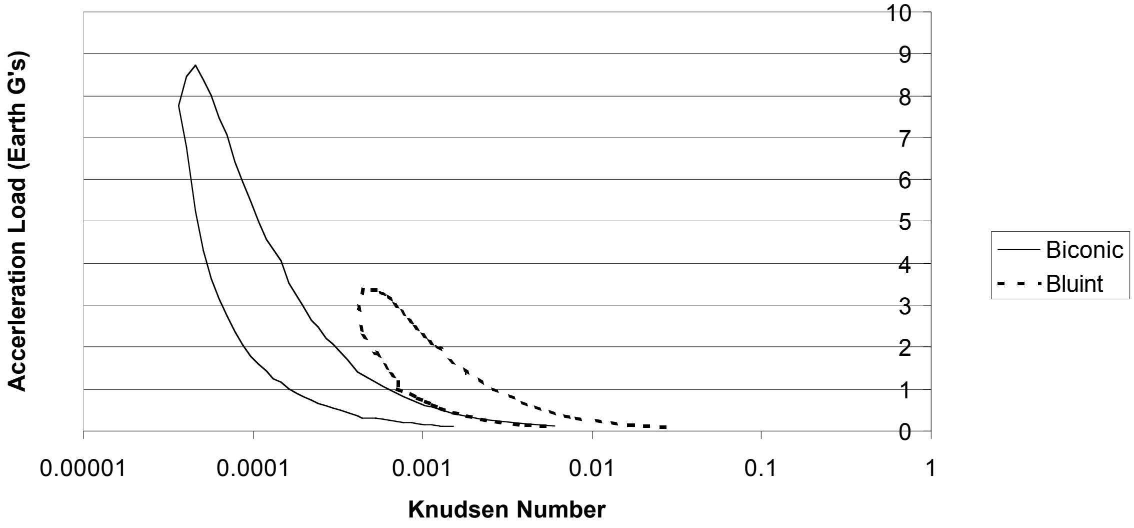

Figure 7. Acceleration Load vs. Knudsen Number

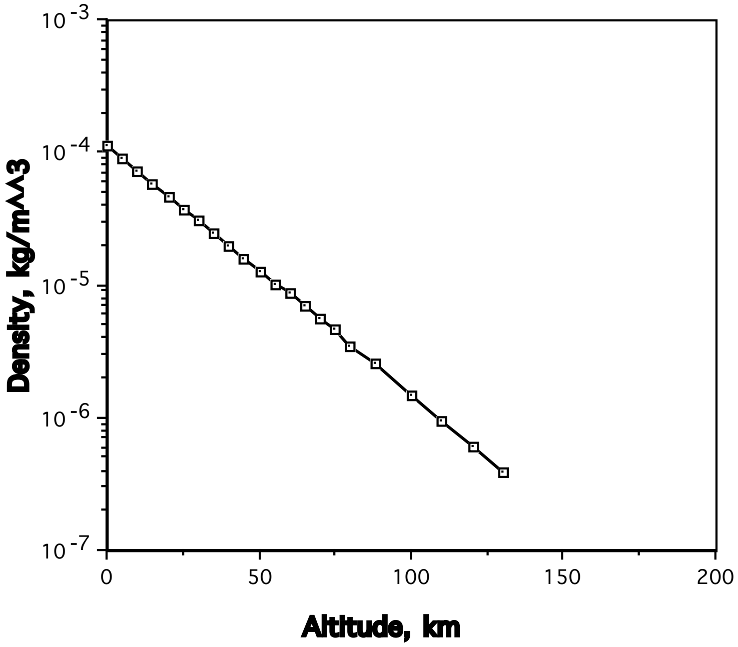

Figure 8. Triton atmospheric density profile

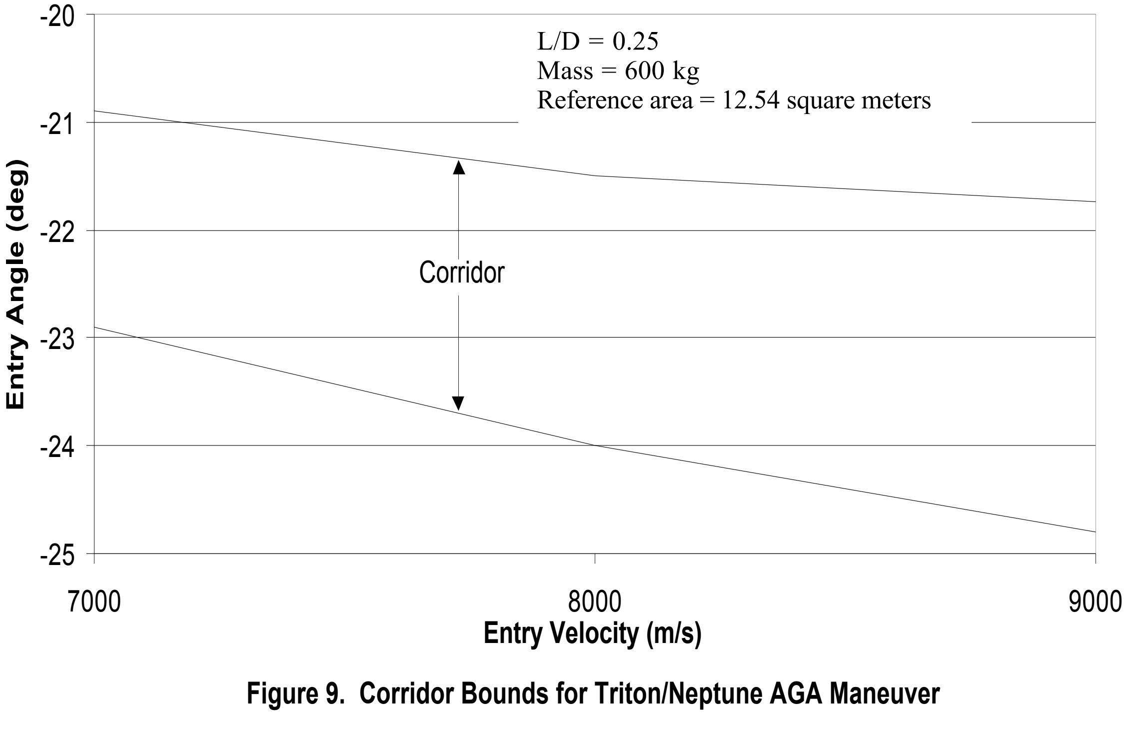

Figure 9. Corridor Bounds for Triton/Neptune AGA Maneuver

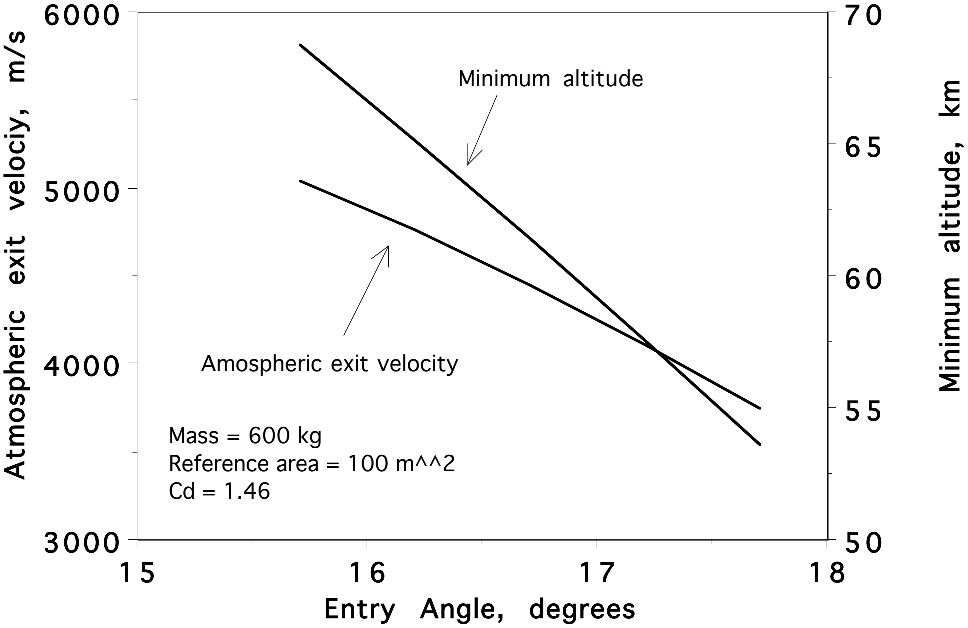

Figure 10. Aerocapture of a ballute at Triton as a function of entry speed