JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 1, January–February 2006

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Investigation of Titan Aerogravity Assist for Capture into Orbit About Saturn

Philip Ramsey* and James Evans Lyne†
University of Tennessee, Knoxville, Tennessee 37996

Introduction

AEROCAPTURE has been studied extensively for application on manned Mars missions,[1,2] and, more recently, for robotic probes to Neptune and Titan.[3,4] However, use of traditional aerocapture at the gas giants has limited appeal because of very high atmospheric entry speeds, severe aerothermal heating, and heavy ablative heat shields.[5]

The present study considers the application of a related maneuver known as an aerogravity assist (AGA), in which the atmosphere and gravitational field of Titan would be used to decelerate a spacecraft and deflect its trajectory, resulting in capture into a closed orbit about Saturn. Because of its high atmospheric density, Titan is well suited for such a mission design. This approach is more appealing than capture using the atmosphere of Saturn itself, because of the much lower entry speed at Titan and the lower heating rate and heat load. The less severe aerothermal environment translates directly into weight savings in the vehicle's thermal protection system.

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 (V_T) 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 potential target orbits about Saturn could be achieved by means of a successful AGA at Titan. The final Saturnian orbit will depend on both the orientation and magnitude of the probe's outbound hyperbolic excess speed with respect to Titan (V_∞^T) after the AGA. By lining up the outbound V_∞^T with V_T, an orbit can be reached with a periapsis radius equal to that of Titan's orbit and a higher apoapsis. If the outbound V_∞^T 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).

The proposed strategy could be used on a Cassini-type mission with a Saturnian orbital periapsis of approximately 160,000 km, allowing the probe to pass through the gap between rings F and G. Achieving this periapsis radius will require an outbound V_∞^T of approximately 2.89 km/s, opposite in direction to Titan's orbital velocity vector. However, if V_T and the outbound V_∞^T are collinear, the final spacecraft trajectory about Saturn will lie very near to or in the ring plane. Directing an outbound V_∞^T of 3 km/s opposite to V_T and about 11 deg above the orbital plane would yield a final orbit about Saturn with the apoapsis coincident with the ascending node at Titan's orbital distance, the periapsis coincident with the descending node and passing between rings F and G, and an orbital inclination of approximately 12 deg, thereby avoiding the ring plane.

In this study, we examined atmospheric entry corridors for a variety of vehicles and considered the impact of atmospheric dispersions and variations in the final target orbit on the aerogravity maneuver.

Methodology

The entry corridor for a traditional aerocapture maneuver is defined as the range of atmospheric entry flight path angles that can result in successful capture into a desired target orbit. For the present study this definition is slightly modified so that the target is not a closed orbit about Titan, but a specified hyperbolic excess speed with respect to Titan that results in a closed orbit about Saturn. The shallow end of this corridor is defined by the overshoot boundary; for the present study we find this limit by simulating a full lift-down trajectory and adjusting the entry angle until the exit velocity meets the desired target value. Similarly, we find the steepest possible angle (the undershoot boundary) by simulating a full lift-up trajectory and adjusting the entry angle until the vehicle's atmospheric exit velocity satisfies the target value. No deceleration or heating constraints are imposed on the trajectories.

Trajectory simulations were conducted using the three-dimensional version of the Program to Optimize Simulated Trajectories (POST).[6] The nominal, minimum, and maximum density atmospheric profiles for Titan were taken from Yelle et al.[7] and are shown in Fig. 2. Atmospheric entry speeds (V_E) of 6 to 10 km/s were examined, corresponding to inbound values of V_∞^T ranging from 5.54 to 9.73 km/s. The large range of V_E considered allows the study results to be applicable over a wide variety of potential interplanetary trajectories and approach geometries. Trajectory simulations were begun at an altitude of 905 km with due east equatorial entries. A vehicle mass of 600 kg was used, and four aerobrake configurations

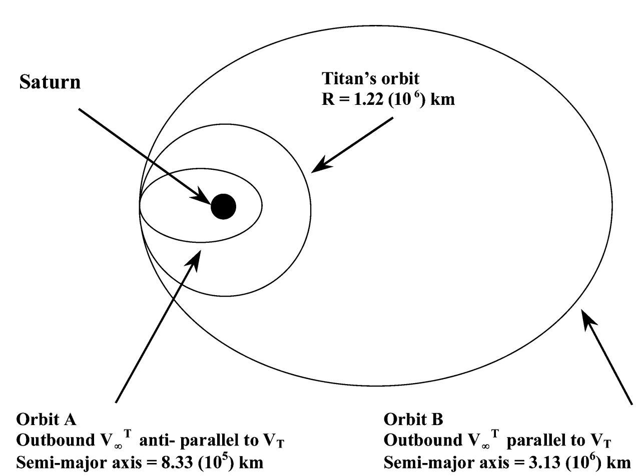

Fig. 1 Potential variation in final Saturnian orbit for outbound V_∞^T 1.5 km/s.

Presented as Paper 2003-644 at the AAS/AIAA Astrodynamics Specialists Conference, Big Sky, MT, 3–7 August 2003; received 17 March 2004; revision received 15 April 2005; accepted for publication 27 April 2005.

*Graduate Student, Department of Mechanical, Aerospace and Biomedical Engineering. Student Member AIAA.

†Associate Professor, Department of Mechanical, Aerospace and Biomedical Engineering; jelyne@utk.edu.

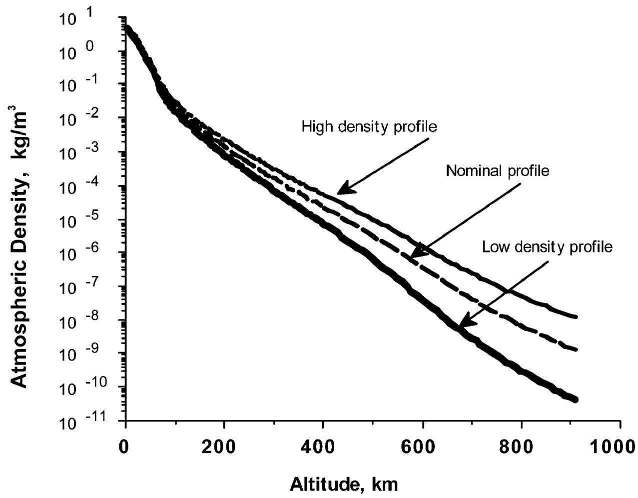

Fig. 2 Titan atmospheric density profiles from Yelle et al.[6]

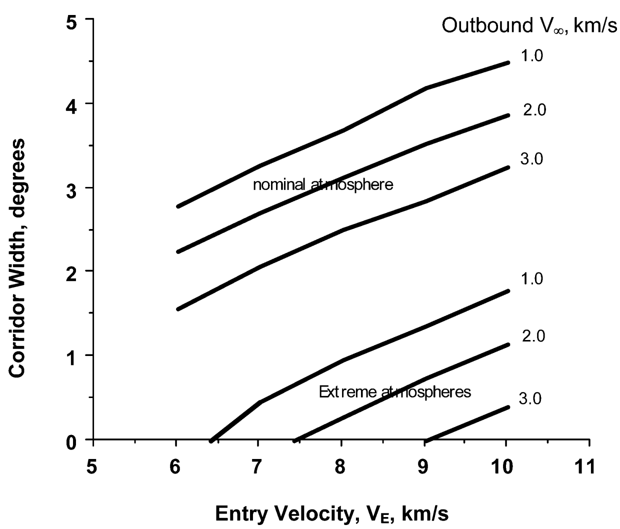

Fig. 3 Corridor width vs entry velocity for a probe with *L/D* 0.25.

were evaluated: a biconic with a continuum L/D of 1.0 and a reference area of 3.14 m^2 and three blunt bodies with continuum L/Ds of 0.25, 0.39, and 0.48 and reference areas of 12.56 m^2. (Transitional and free-molecular aerodynamics were not considered.) The vehicle was targeted to outbound values of V_∞^T ranging from 1.0 to 3.0 km/s. Thus far, no constraints have been placed on the direction of the outbound V_∞^T. Simple two-body mechanics and patched-conic analysis were used to determine the trajectory once the vehicle left Titan's atmosphere.

Results

The corridor width for an L/D of 0.25 is shown in Fig. 3 as a function of entry velocity for both the nominal and extreme atmospheric models and for three target values of the outbound V_∞^T. 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. Because the density profile that 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, navigation knowledge errors, and uncertainties in the expected aerodynamic performance of the vehicle. Current estimates indicate that insertion angle errors of ±0.9 deg are to be expected. Therefore, a corridor width of 2.0 deg is the minimum considered acceptable for this study. Improvements in interplanetary navigation capabilities that result in a more precise

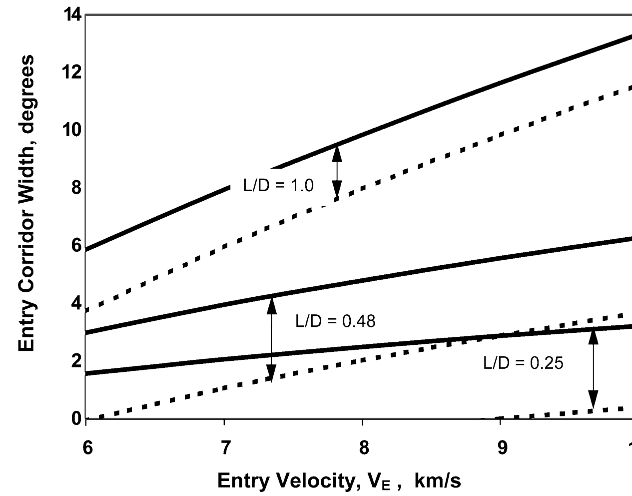

Fig. 4 Titan/Saturn AGA maneuver corridor width vs entry velocity for various vehicles: ——, nominal atmospheric density profile and - - - -, extreme atmospheres.

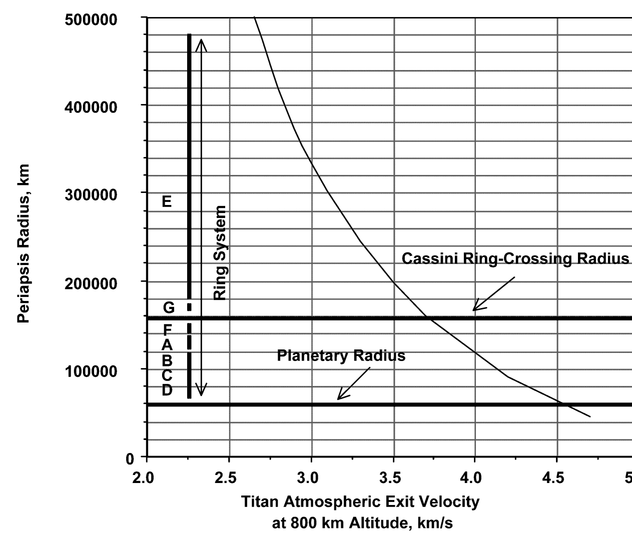

Fig. 5 Periapsis radius of final Saturn orbit vs spacecraft atmospheric exit velocity at Titan. Outbound V_∞^T is opposite in direction to V_T.

insertion angle might allow this corridor requirement to be relaxed. It is apparent that an increase in the targeted outbound V_∞^T from 1.0 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 final orbital energy increase. This trend results from the decreased control the vehicle can exert over its trajectory as the duration of the atmospheric pass and the required energy loss are reduced.

If we assume that a 2-deg, corridor is required, the choice of entry velocity and outbound V_∞^T determines whether a given L/D is adequate. For the previously described Cassini-type target orbit with a periapsis between rings F and G, the outbound V_∞^T will need to be near 3 km/s, and a lift-to-drag ratio higher than 0.25 will be required. Figure 4 shows corridor widths for three values of the L/D, assuming an outbound V_∞^T of 3.0 km/s. The arrows 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.

Figure 5 indicates the sensitivity of the final Saturn orbit to variation in the atmospheric exit speed. Although the slope of this curve is a strong function of the alignment of V_T and the outbound V_∞^T of the probe, it is apparent that precise targeting of the atmospheric exit velocity (and outbound V_∞^T) will be required to achieve the desired target orbit.

Aerodynamic heating was not calculated as part of this preliminary study. However, work has been carried out previously at NASA Ames to evaluate the aerothermal environment during Titan aerocapture.[3] The atmosphere is approximately 95% nitrogen and 5% methane; the presence of methane results in substantial radiative heating, well above the convective contribution. Unfortunately, there remains considerable uncertainty in the radiative computations. However, the aerothermal environment for the proposed mission is likely to be less severe than for capture into orbit about Titan itself, because the vehicle departs Titan with a finite V_∞ and, therefore, undergoes a smaller energy loss during the atmospheric trajectory. Vehicle decelerations are typically modest, with an undershoot trajectory for the biconic vehicle entering at 8 km/s peaking near 13 G.

Future Work

Substantial work must be devoted to determining the optimal Titan approach, the required turn angle during the maneuver, and the L/D necessary to carry out the turn. The results will be highly dependent on the target orbit about Saturn. An approach with the vehicle and Titan initially traveling in the same direction would lessen the atmospheric entry speed, but would require a turn of nearly 180 deg to achieve a low periapsis altitude about Saturn. Such a large turn would increase the duration of the atmospheric trajectory and might require a higher L/D than an oblique approach. A complex trade-off study will be required to select a strategy that yields the least severe aerothermal environment and the lightest weight aerobrake. For example, which would be lighter, a biconic entering at 8 km/s and executing a nearly 180-deg intra-atmospheric turn or a blunt configuration entering at 11 km/s but having a considerably shorter duration atmospheric trajectory?

It will also be important to determine the feasibility of accurately targeting the direction as well as the magnitude of the outbound V_∞^T. Targeting both of these variables while allowing for potential atmospheric dispersions will require a Monte Carlo-type study using a predictor–corrector guidance algorithm similar to that described in Refs. 1 and 2. A closely related task will be the evaluation of post-capture propulsion requirements for orbital clean-up. In addition, the impact of Saturn's gravitational field on the maneuver must be evaluated using a code that allows for multibody dynamics. Last, the potential use of this type of maneuver for orbital capture at the Neptune/Triton system should be considered.

Conclusions

Orbital capture about Saturn using a Titan aerogravity assist maneuver appears to be feasible. Depending on the choice of the final Saturn orbit and the atmospheric entry speed at Titan, blunt aeroshells or vehicles with midrange L/D (such as biconics) offer adequate entry corridors, even when atmospheric dispersions are accounted for. Deceleration loads are modest, and aerodynamic heating should be less than that associated with capture into orbit about Titan itself. A vehicle using this strategy could reach a wide range of final orbits about Saturn but must accurately target both the direction and magnitude of V_∞ as it departs Titan.

References

[1] Jits, R. Y., and Walberg, G. D., "Blended Control, Predictor–Corrector Guidance: An Enabling Technology for Mars Aerocapture," International Astronautical Federation, Paper IAF-01-A.7.05, Oct. 2001.

[2] Braun, R. D., Powell, R. W., and Lyne, J. E., "Earth Aerobraking Strategies for Manned Return from Mars," *Journal of Spacecraft and Rockets*, Vol. 29, No. 3, 1992, pp. 297–304.

[3] Lockwood, M. K., "Titan Aerocapture Systems Analysis," AIAA Paper 2003-4799, July 2002.

[4] Jits, R. Y., Chen, Y. K., and Wright, M. J., "Trajectory Analysis for Thermal Protection System Design of Neptune Aerocapture Vehicle," Paper IAC-02-Q.2.06, Oct. 2002.

[5] Lockwood, M. K., "Neptune Aerocapture Systems Analysis," AIAA Paper 2004-4951, Aug. 2004.

[6] Brauer, G. L., Cornick, D. E., Olson, D. W., Peterson, F. M., and Stevenson, R., "Program to Optimize Simulated Trajectories (POST)," NASA CR NAS1-18147, Sept. 1989.

[7] Yelle, R. V., Strobell, D. F., Lellouch, E., and Gautier, D., "Engineering Models for Titan's Atmosphere," *Huygens: Science, Payload and Mission*, ESA SP 1177, ESTEC, Noordwijk, The Netherlands, 1997, pp. 243–256.

C. Kluever
Associate Editor