INCREASING LUNAR PROPELLANT DELIVERY CAPABILITY WITH ACES AEROBRAKING

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Introduction: As the commercial space industry continues to grow, many are looking out from Low Earth Orbit (LEO) for opportunities in the neighborhood of Cislunar space. Fueling such activities is the potential of refining space-mined volatiles into rocket propellants. This prospect has long been thought to be an enabling factor to breaking the paradigm of massively expensive transportation in space. Creating this reality means having space miners and resource processors as well as transportation vehicles that can operate for long durations in the space environment.

In 2015, a landmark announcement in the history of commercial space was made by United Launch Alliance (ULA), where ULA offered to be a customer for space-based propellants if they could be mined and processed at a price equating to competitive values in LEO[1]. This follows ULA's development of the Advanced Cyrogenic Evolved Stage (ACES), replacing their long running Centaur upper stage. The ACES represents a capable transportation vehicle, designed to be refuelable and fully powered with cryogenic propellent.

A 2016 study on the possible growth of the space economy estimated the cost of transporting propellant from the Earth-Moon Lagrange point 1 back to LEO on a regular basis[2]. Doing so requires shedding over 3.5 km/s to enter a circular LEO orbit. This much deceleration requires large amounts of propellant, which quickly increases with the payload mass. Alternatively, the study considered aerobraking cargo spacecraft into LEO. Significant savings were seen even by using a combination of propulsive and aerodynamic deceleration. These results are summarized in Figure 1.

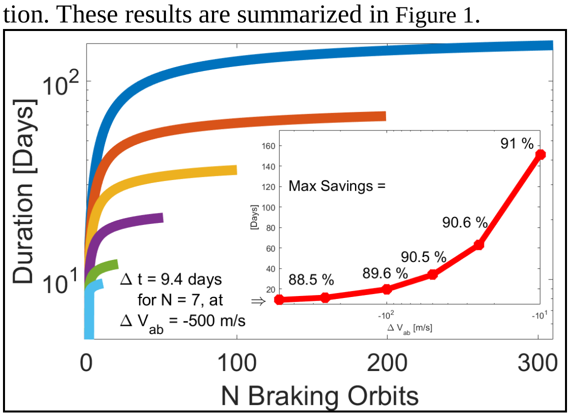

Figure 1. Results of basic aerobraking analysis[2]. Each curve corresponds to a level of aerobraking deceleration per pass (orbit) and has a corresponding point in the subplot for the optimal conditions. This simplified analysis does not model the continuously variable thermal environment during the maneuver and the thermal loads on the propellent. A major trade-off to consider is propellant saved from aerobraking relative to the increased levels of boiloff and material wear from the increased aerothermodynamic heating of short duration (high deceleration per pass) as well as the opposite extreme with durations on the order of months.

ULA recently teamed with CU Boulder to study the complexities of aerobraking the ACES in order to verify feasibility of improved delivery capabilities for the in-space propellant market. The following sections review major modeling efforts to explore the relevant parameter space and apply these findings to the business case for space of ULA.

Modeling: Understanding the vehicle thermal-loads distribution includes a variety of heating sources in the aero-space environment that depend on the vehicle location, and its dynamic and thermal states. Scenario analysis includes three modeling categories. First is the *flight dynamics of the spacecraft at orbital velocities in and out of the Earth's atmospheric density field*. This provides insight into the dynamic loads throughout the vehicle maneuver as well as improved estimates of the overall transfer duration. Modeling the flight trajectories requires the second scenario category, *system identification of a high speed flight vehicle*. This topic falls to aerothermodynamic modeling which includes both the pressure forces defining the aerodynamics and the heating effects of high speed flight. Finally, the *feedback of the spacecraft material to the heating rates at various points in the maneuver must be integrated*. In each category, efficient databasing and interpolation schemes are paramount in enabling the full maneuver simulation to remain computationally feasible.

Spacecraft dynamics. The focus of this effort is in finding optimal aerobraking trajectories in order to characterize and quantify the realistic benefits and drawbacks of aerobraking for commercial operations. A variety of approaches have been applied to understand both isolated segments of the trajectory as well as the entire maneuver. The preliminary analysis (Figure 1) used a coupled-scheme of keplarian motion in space and a skip-entry solution for simplified atmospheric flight [2]. Optimization schemes including shooting methods and collocation techniques [4] have been applied. A multi-step procedure is implemented with entry conditions databased from multiple single-pass trajectory simulations. An interpolant can then be created, removing the need to iterate apogee through atmospheric propagation in-loop, thus decreasing the computational load of analyzing the full transfer.

Aerothermodynamics. A combination of common techniques for studying the aerothermodynamics is applied to the system identification of a simplified ACES geometry. This entails generating aerodynamic and heating characteristics in terms of nondimensional coefficients, for various steady state flight conditions. These data are used in the trajectory models discussed previously, as well as the thermal response modeling presented next. A number of simplifying assumptions were implemented in generating these initial databases, as discussed in past works [3]. The authors are reviewing these simplfications and updating the databases with higher fidelity predictions.

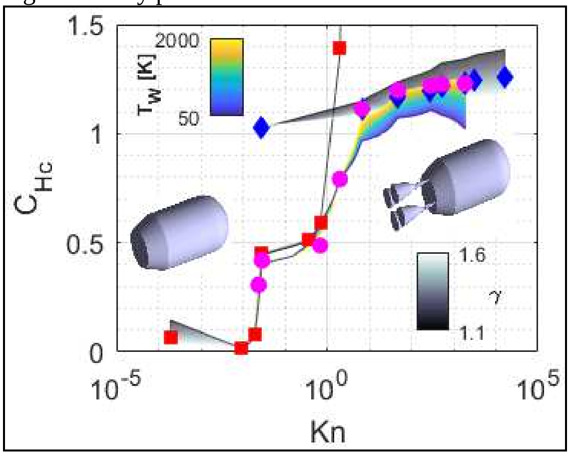

Figure 2. Convective heating coefficient (total power absorbed) as a function of freestream Knudsen number. Panel methods used the simple ACES tank body (left) while the DSMC results included the more complex tank with rocket geometry (right).

Figure 2 shows the resulting variation of computed convective heating coefficients by the three methods used. Two panel methods, for Free-Molecular and Modifed Newtonian idealizations, are show as diamond and square symbols, respectively. These were varied over a range of specific heat ratios to estimate the range of real gas effects shown with gray shading. Strong divergence of these methods can be seen near a Knudsen number Kn = 1. Bridging this gap is a more accurate estimate provided by the Direct Simulation Monte Carlo (DSMC) method, shown as circles. The colored shading shows the interpolant generated from the resulting database and provides an indication of how wall temperature affects the resulting heating coefficient. The highly nonlinear nature of these various methods shows the complexity of properly characterizing a body for aerobraking maneuvers.

Thermal response and propellant boiloff. As a limiting factor, materials need to handle the fluctuation of pressures and temperatures that would be experienced by an aerobraking spacecraft. The ability to vary the material properties and study the amount of energy that reaches the propellant is vital in realizing the feasible range of operation. First, single pass trajectories can be used to understand the upper limit based on a given material selection. Example solutions for a range of entry conditions is shown in Figure 3, for a vehicle with no added thermal protection.

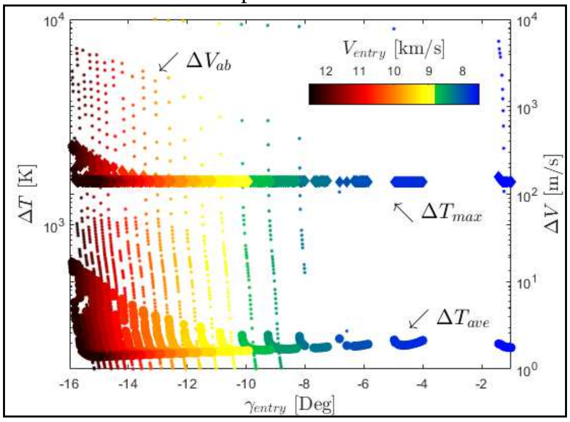

Figure 3. Variation of temperature and velocity as a function of entry conditions.

Also included is the aerobraking decrease in velocity (show as a positive value on the right). It is clear that for a given entry velocity, a small variation in the entry flight path angle, γ_{entry}, can result in large changes in deceleration and heating. From these single-pass results, the full maneuver can be designed and simulated to understand the extent of thermal fluctuation and propellant boiloff rates.

Cost Implications: Providing a kilogram of resource in LEO for a lower cost than from Earth is essential to creating a successful space-based market. The work discussed here allows cost implications of aerobraking to be properly quantified. Shorter duration and larger payloads result in more cost towards thermal protection systems. Such significant propellant savings however provide adequate margin to engineer cost effective solutions. This means ULA is able to purchase propellant at a higher cost while remaining competitive to Earth based resource prices in LEO. Making the resource harvesters operation more financially viable. In a possible future of regular cislunar transportation, competing companies will find significant advantages by incorporating aerobraking into their business plans.

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