Aerobraking Technology for Earth Orbit Transfers

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Abstract. This paper addresses the development of an innovative aerobrake concept that utilizes the drag caused when a spacecraft dips into the upper atmosphere to change orbits inexpensively and with little or no propellant expenditure. This patented process (U.S. Patent # 6,286,787 issued 11 Sep 2001) enables small satellites to launch using low-cost secondary payload slots on large launch vehicles yet still reach a custom orbit to perform their mission.

This paper presents analysis of the orbit transfer process using an aerobrake device. This includes detailed trajectory simulations that incorporate atmospheric and lunar effects. A detailed trajectory analysis of a sample mission reviewing atmospheric effects and uncertainties (altitude/density variations with sunspot activity, etc.) is presented, along with a method for planning appropriate aerobraking trajectories. The attitude dynamics of the shuttlecock-shaped vehicle during aerobraking passes are presented. Model results from analysis tasks performed in collaboration with NASA Langley Research Center (LaRC) are presented.

This paper discusses technical development performed to date, analysis, component selection, preliminary design, and the path to flight on the first Small Payload Orbit Transfer (SPORT™) system mission. AeroAstro is currently working with the Space Vehicles Directorate at the Air Force Research Lab, with commercial funding contributions from a third party, to study the use of a deployable aerobrake to perform orbit transfers from high energy to low energy orbits.

Introduction

With the successful NASA Magellan, Mars Global Surveyor and Mars Odyssey missions, aerobraking has become an established means for orbital maneuvering. Based upon these successes, AeroAstro is working with AFRL and NASA LaRC to bring this technology to commercial availability. The first step in this commercialization is the application of aerobraking technology (U.S. Patent # 6,286,787 issued 11 Sep 2001) to the commercial Small Payload ORbit Transfer (SPORT) vehicle being developed by AeroAstro and ATSB. SPORT uses a large deployable aerobrake structure to generate atmospheric drag that, over the course of about 30 days, transfers SPORT and its payload from GTO to LEO.

While previous aerobraking missions have used traditional style solar arrays as their aerobraking surfaces, the unique requirements of aerobraking at Earth have driven AeroAstro to a dedicated aerobraking structure. The combination of commercial incentives to rapidly deliver the payload to its destination and the radiation risk posed from repeated passes through the Van Allen belts restricts the duration of the aerobraking mission to around 30 days. This time constraint and the large transfer ΔV from GTO and LEO drives the SPORT design to a very small ballistic coefficient. The SPORT mission characteristics are compared to those of previous aerobraking missions in Table 1.

A small ballistic coefficient has two main implications to the design of the SPORT aerobrake. The first is that the aerobrake must provide a profile area that is very large in comparison to the spacecraft mass. The second is that the mission operations will be substantially faster than previous missions, with large changes in the orbital parameters occuring with each pass. This paper addresses the implications of these challenging mission requirements.

Table 1. Aerobrake Mission Comparison

	Magellan	MGS	Odyssey	SPORT[†]
Mission Duration, days	70	298	75	30
Total ΔV, m/s	1,208	1,217	1,080	2,504
Mass, kg	1100	760	448	120 / 600
Profile Area, m^2	23	17	11	30 / 150
Ballistic Coefficient	~22	~22	~20	1.9

† The SPORT product line consists of several sizes corresponding to the secondary payload opportunities, which are bounded by the data in this table.

Aerobrake Design

The need for a large, load-bearing structure that fits within the small volume and mass constraints typical of small and micro satellites has led AeroAstro to develop a unique large deployable structure for SPORT. Using a combination of commercial and AFRL SBIR funds, AeroAstro has been working for over two years on the details of how to design, fabricate, package and use a large deployable aerobrake. While a full treatment of this topic is beyond the scope of this paper, a summary of the structural design status is provided, including information on each of the options being considered.

Configuration

To achieve this large profile area, AeroAstro worked with L'Garde to investigate a variety of aerobrake configurations, including balloons, torus, ballutes, shuttlecock and flat panels, some of which are shown in Figure 1. As a result of this examination, a shuttlecock configuration was selected since it provided good profile area per unit mass, and was shaped to provide aerodynamic stability and hence protection of the payload from the aerobraking environment, without hindering the payload deployment. With the selection of the shuttlecock configuration, shown in Figure 2, the development effort focused on the selecting the structural technology for the aerobrake booms.
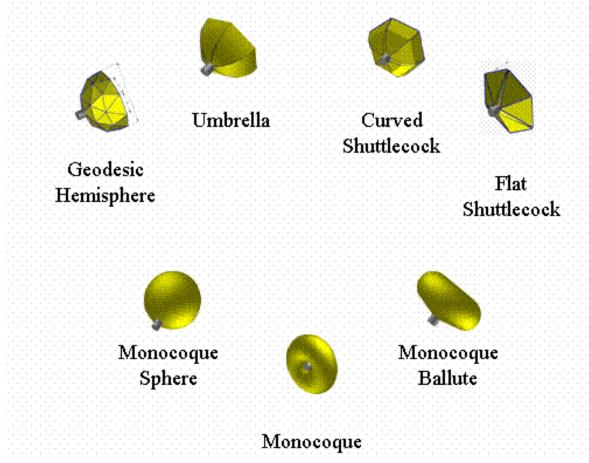

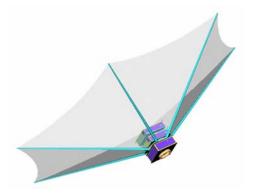**Figure 1. Some Configurations Considered for the SPORT Aerobrake (Courtesy of L'Garde)**

Figure 2. Selected SPORT Aerobrake Configuration

Deployment Schemes

Several deployment schemes are being considered for the aerobrake, including radial telescoping, radial twisting, spiral wrapped and side folded.

Radial Telescoping

In this deployment scheme, shown in Figure 3, the booms are deployed along their axes, but without twisting. This approach provides a very smooth and controlable deployment approach. This scheme is most appropriate to inflatable boom technology.

Figure 3. Telescoping Boom Approach

Radial Twisting

This scheme, shown in Figure 4, has been widely used for antenna and sensor deployment, but the rotation of the boom shaft around its axis during deployment provides a significant complication to the aerobrake deployment due to the suspension of panels between adjacent booms.

Figure 4. Radial Twisting Approach

Spiral Wrapped

In this deployment scheme, shown in Figure 5, the booms are spirally wrapped around a central hub. When released, the booms unwrap from the hub.
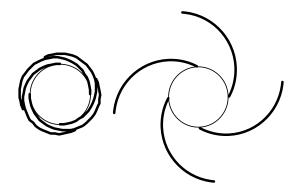

Figure 5. Spiral Wrapped Approach

Side Folded

In this scheme, shown in Figure 6, the booms are individually folded down the sides of the spacecraft. When released the Z-folded booms deploy radially.
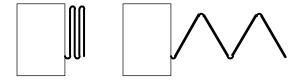

Figure 6. Side Folded Approach

Aerobrake Structure

A variety of boom structure and membrane panel technology options have been evaluated during the development of the SPORT aerobrake. A summary of the boom options is provided in Table II at the end of this section.

Inflatable Booms

Several inflatable boom concepts were considered, including simply inflated tubes, UV rigidizing tubes, Sub-Tg (i.e., below glass transition temperature) rigidizing tubes, and stretched aluminum tubes. While the boom

technologies offered good strength and stiffness for the volume required, the complexity of the inflation and rigidization systems and this solution's mass efficiency were an issue. Figure 7 shows an example of a telescopic inflatable boom .

**Figure 7. Telescopic Inflatable Booms
(Courtesy of L'Garde)**

Elastic Booms

Several elastic boom technologies have been examined, including shape memory tubes, split cylinders, and lenticular booms. Rather then relying on gas inflation, these booms rely on storage of potential strain energy for deployment. While a promising option, the low maturity of the shape memory tube technology and the need to heat the boom during deployment led to its elimination.

The split cylinder technology uses a rigid tube with small axial slits in the tube wall, where a boom fold is desired. An example of how a split cylinder tube can be folded for storage is shown in Figure 8. Further examination is needed to determine the viability of this approach.
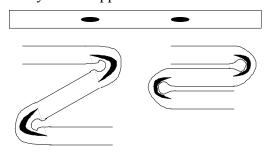

Figure 8. Split Cylinder Folding

The lenticular boom technology, shown in Figure 9, uses a pair of opposing carpenter tapes joined along their edges. By compressing the tapes, the lenticular boom can be wrapped flatly around a central hub.
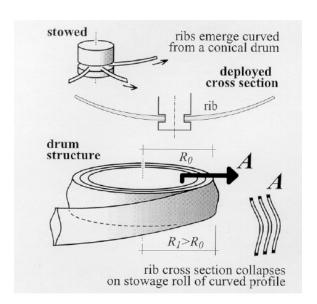

**Figure 9. Lenticular Boom Stowage
(Courtesy of L'Garde)**

While the elastic booms offer a simple and reliable deployment approach, there are concerns about the risk of damaging the aerobrake panels from overly energetic boom straightening. Implementation of this technology may also require techniques to control and slow down the deployment, through the use of dampers, friction, or incremental deployments.

Mechanical Hinged Booms

A more traditional approach to deployable booms is to use mechanical hinges between rigid tube segments. Several versions of this approach have been considered, including simple spring loaded hinge, tent pole (concentric cylinders with guide line), and spring loaded cup/cone. Of these options, the cup/cone approach is being examined further, since it offers the best boom stiffness, and is shown in Figures 10 and 11.

While the mechanical hinged boom offers a simple and proven deployment approach, there are critical packaging issues that have to be addressed. The first is that the boom has to be stacked in several sections to allow it to fold within the envelope limits. Since this stack of tubes does not flatten, the stowed boom requires substantially more volume than any of the inflatable or elastic boom options that collapse when stowed. Additionally, several parts are required at each hinge joint, which are a potential reliability concern.
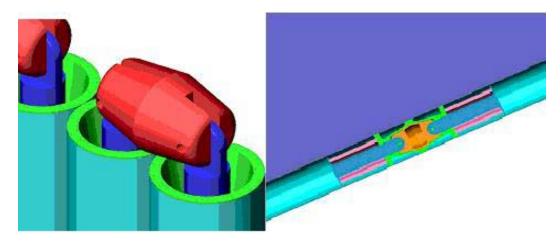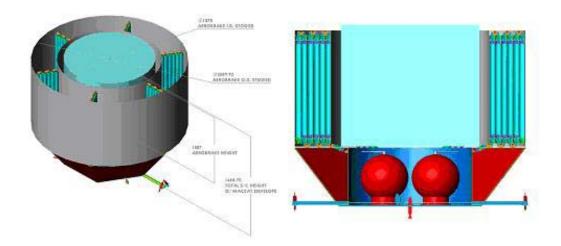

Figure 10. Cup and Cone Mechanical Hinge

Figure 11. Side Folded Stowe Aerobrake

Membrane Panels

A range of membrane panel technologies are being considered for the aerobrake. These technologies include a simple reinforced polyimid panel, to a multi-layer reinforced polyimid panel, to a woven fabric material.

The exact nature of the panels will be determined as the structural loading and the mass and volume limitations are refined.

Additionally, the panels will incorporate design features to protect from static charge build up, atomic oxygen erosion, and for thermal management. In future SPORT vehicles, the

aerobrake surface will be used for power generation, after being integrated with thin film solar panels. While the design of the aerobrake can accommodate sufficient cell coverage to provide primary spacecraft power, it is anticipated that the first SPORT flight will only utilize a limited cell coverage area for technology validation purposes.

One of the key issues facing the design of the membrane panels is the balancing of tensile strength with the volume and mass limitations of micro-spacecraft. Since the leading boom candidates have limited deployment control, there could be significant loads imparted to the membranes when the booms snap into place. While robust panels could eliminate this issue, the packaging volume and mass limitations of microspacecraft drive the design to a compromise.

Table 2. Summary of Boom Structure Options

	Inflatables	Elastic Structures	Mechanical Hinges
Advantages	Compact packaging Ultra low mass	Compact packaging Low mass Low part count Simple deployment	Moderate mass Simple deployment
Disadvantages	Requires inflation and rigidization systems High part count	Limited deployment control	Poor packaging High parts count Limited deployment control
Conclusions	Inflation and rigidization complexities outweigh the mass and volume advantages	Good packaging, low mass, and low part count make this a good candidate	High part count and poor packaging limit the applicability of this option

Mission Design

Nominal Mission

The SPORT nominal mission starts with a launch to a roughly equatorial Geostationary Transfer Orbit (GTO) using an auxiliary payload slot on an Ariane 5 launch vehicle. The orbit is only roughly equatorial because its nominal inclination is 7 degrees. The nominal apogee and perigee altitudes in GTO are approximately 35,786 km and 400 km, but each of these may vary up or down by a few hundred km depending on the primary payload's particular requirements. Immediately after launch the apogee is nominally directly between the Earth and the sun, so as the one to two month mission progresses and the Earth moves around the sun, the sun-line will precess towards the side of the orbit that approaches perigee, this effect is exacerbated by the increasing

precession rate of the orbit as the apogee is lowered due to aerobraking.

Once the spacecraft has been checked-out in its initial GTO orbit, a sequence of burns are performed at successive apogees in order to lower the perigee altitude to approximately 200 km – which is just 50 km above the nominal initial aerobraking perigee altitude of 150 km, yet still high enough to effectively avoid any significant atmospheric effects. At this point the apogee velocity should be at its slowest, which makes it the appropriate time to perform any small inclination changes that may be desired – assuming of course that the apogee coincides with the ascending or descending node of the orbit as it frequently does.

Once any inclination changes have been performed the lightweight aerobrake is deployed and checked out. After deployment, a sequence of test firings will be perfomred with the main engine in order to characterize the coupling of

the deployed aerobrake's flexible body modes with fuel sloshing and engine firing. It is critical that the aerobrake's flexibility be limited such that the vehicle's overall center of mass does not stray too far from the thrust axis, and therefore structure stiffness is a significant driver for the design.

Once the vehicle with the deployed aerobrake has been checked out, the aerobraking phase of the mission is initiated. A sequence of burns are performed at apogee in order to slowly walk-in the perigee altitude from 200 km down to the nominal initial aerobraking altitude of 150 km. The walk-in burns are conducted such that the perigee is lowered 5 to 10 km at a time, with a few orbits in between each lowering used to make observations, to study the aerobraking data and update mission models accordingly. With the perigee safely at 150 km and aerobraking ongoing, the operations staff simply watches the apogee rapidly drop due to aerobraking.

During the course of normal aerobraking the perigee altitude naturally varies due to semi-predictable atmospheric variations as well as due to more predictable classical orbit perturbations: lunisolar gravity, solar radiation pressure and Earth's own higher order gravity effects (J2 and far higher). It is incumbent upon the operations staff to continuously estimate the perigee altitudes using GPS and occasionally perform small burns at apogee in order to prevent the perigee from straying too far (~ ± 5 km) from it nominal altitude – or out of the safe perigee 'corridor'. As the apogee altitude drops, the safe perigee corridor rises to higher altitudes and additional small burns are made at apogee as needed. The method for selecting the safe perigee corridor is presented in the Mission Dynamics section.

At the beginning of the main aerobraking phase (after walk-in) the orbit period is long and the perigee velocity is high, so aerobraking passes are widely spaced in time, only lasting a short duration and produceing a strong drag force. Towards the end of the main aerobraking phase the orbit period is short and the perigee velocity is low, so the aerobraking passes are spaced closer together, last longer and produce less drag force. The net result is that the apogee altitude decreases roughly linearly with time over the course of the entire main aerobraking phase, not counting walk-in or walk-out.

Through discussion with several customers AeroAstro and ATSB have learned that the entire transfer mission must be accomplished in ≤ 30 days in order to limit the payload's total ionizing dose (TID) to a very stringent ≤ 2.5 krads. Since typical LEO circular orbits are in the range from approximately 300 to 1000 km altitude, the apogee altitude must drop from ~35,786 km down to ~700 km in ≤ 30 days, resulting in a conservative estimate that the apogee will drop ~1,170 km per day. Since the apogee would be dropping at such a high rate, and typically in increments of ~100 km per pass towards the end of the mission, it is desirable to slowly walk-out the perigee altitude upwards and away from the denser atmospheric regions so as to slow down the rate at which the apogee drops such that the desired final apogee of ~700 km may be accurately achieved with a minimum expenditure of fuel. As usual, the required maneuvers to walk-out the perigee are accomplished by making small burns at apogee.

During the final parts of the mission the perigee altitude is further raised all the way up to the apogee altitude to circularize the orbit. If required, orbit parameters such as altitude and true anomaly may be trimmed at this point. When the mission operations team is satisfied that the best possible orbit has been achieved, the SPORT vehicle deploys its payload, performs a collision and contamination

avoidance maneuver, and uses all of its remaining fuel (apart from residuals) to lower its altitude for decomissioning purposes, in a controlled de-orbit.

Aerodynamic Characteristics

AeroAstro has been working closely with the staff at the NASA Langley Research Center (LaRC) in analyzing the complex transition-regime aerodynamic flows involved with aerobraking. The LaRC staff have gained extensive experience analyzing aerobraking problems on past aerobraking missions such as Mars Global Surveyor and Mars Odyssey.

To date, LaRC has contributed to the SPORT effort by performing Direct Simulation Monte Carlo (DSMC) aerodynamic computations using their Beowolf cluster. Their computations incorporate all significant effects of atmospheric energetic molecules colliding with the SPORT vehicle surfaces (Figure 12) and material effects. The data generated by LaRC has included the variation of the drag coefficient with Knudsen number (Figure 13) as well as a full aerodynamic

database of force and moment coefficients at all attitudes for the nominal Knudsen number. Figure 14 shows data computed using a subset of the moment coefficient database. In the area of structural and thermal analyses, LaRC has provided data describing the distribution of pressure and shear loads over the aerobrake surface as well as the variation of the heat flux and heat transfer coefficient over the aerobrake surface at various Knudsen numbers (Figures 15 and 16).

In addition, staff at LaRC Vehicle Analysis Branch are performing analysis of the overall mission using the aerodynamic data and the latest version of their in-house trajectory tool called POST-2 (Program to Optimize Simulated Trajectories). LaRC's overall mission analysis will be compared to AeroAstro's own overall mission analysis which is being conducted using STK software (Satellite Tool Kit by Analytical Graphics Inc.). AeroAstro's analysis takes advantage of the latest STK v4.3 features that enable incorporation of LaRC's aerodynamic data as needed. Some results of AeroAstro's ongoing mission analyses using STK and Matlab together with LaRC's data are presented in the Mission Dynamics section.
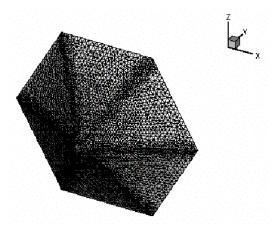

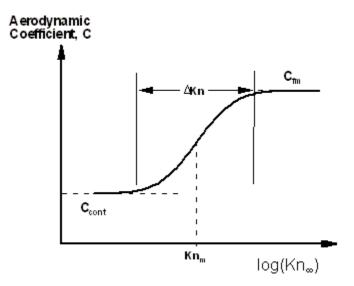**Figure 12. Simplified SPORT Geometry used for DSMC Computations (Courtesy NASA LaRC)**

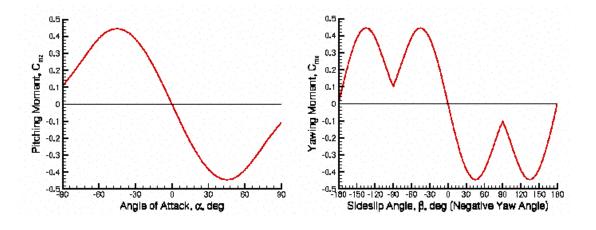**Figure 13. Expected Variation of Aerodynamic Coefficients with Knudsen Number (Courtesy NASA LaRC)**

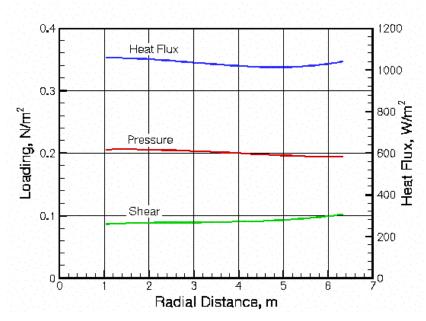**Figure 14. SPORT Static Aerodynamic Stability (Courtesy NASA LaRC)**

Figure 15. Initial DSMC Results at 150 km Perigee (Courtesy NASA LaRC)

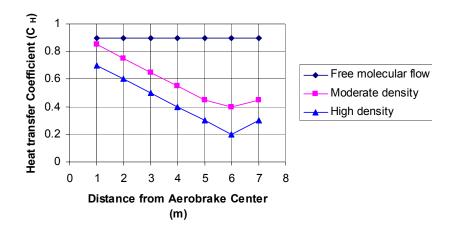**Figure 16. Estimated Generic Heat Transfer Coefficients Across the SPORT Aerobrake**

Mission Dynamics

AeroAstro is performing detailed SPORT mission analyses in order to facilitate the planning of actual missions and in order to aid the proper selection of fundamental design parameters of the reference vehicle configuration. As described in the Nominal Mission section, the mission analysis must determine the safe perigee corridor for any given apogee and ballistic coefficient. The minimum perigee altitude of the safe perigee corridor must satisfy three constraints:

- The natural lifetime of the SPORT vehicle must be ≥ 3 days. Natural lifetime is defined as the duration of time required for SPORT to descend below 100 km altitude if no engine firings are performed.
- The expected heat power flux profile due to aerothermal heating during the aerobraking pass must be survivable by a comfortable margin.

- The expected maximum aerodynamic load (drag force) during the aerobraking pass must be survivable by a comfortable margin. Should the aerodynamic load rise too high, the expected failure points would be the hinges at the bases of the booms which support the aerobrake membrane material.

The maximum perigee altitude of the safe perigee corridor must satisfy two constraints:

- It should be low enough that sufficient aerobraking occurs such that the entire orbit transfer mission is accomplished in ≤ 30 days.
- It should be high enough such that the range between the minimum and maximum perigee altitudes is large enough such that non-impulsive aerobraking and atmospheric/orbit perturbations do not cause the actual perigee altitude to drift so rapidly that corrections (via apogee burns) are required too frequently, i.e., no more than once every day or two.

The aerobrake size must be selected such that the SPORT vehicle (and its payload) of a given mass (constrained by launch vehicle performance) and shape can successfully accomplish the apogee-lowering mission in ≤ 30 days, while also satisfying all the other constraints. This is analogous to selecting the ballistic coefficient C_B.

$$C_B = m / (A_p \, C_D)$$

In the equation above m is the total mass of the vehicle, A_p is the projected area of the vehicle and C_D is the drag coefficient of the vehicle's shape. The analysis is somewhat complicated by the fact that the mass of the vehicle changes by as much as 20% as fuel is consumed at an imprecisley known rate determined by how often perigee altitude adjustment maneuvers of varying sizes are needed. Furthermore, the drag coefficient of the vehicle changes depending on the shuttlecock angle of the aerobrake as well as the Knudsen number at any given point. Figure 17 shows the large variation in Knudsen number experienced during an early aerobraking pass. The shuttlecock angle of the aerobrake must be selected such that sufficient passive aerodynamic stability is achieved during aerobraking, but large angles are difficult to achieve structurally.

AeroAstro has approached this complicated mission analysis problem by creating a high-fidelity simulation of the trajectory using STK. The STK simulation uses the NASA Joint Gravity Model 2 at a nominal degree and order of 21 (out of a possible 70). Lunar and solar gravity perturbations, as well as perturbations due to solar radiation pressure are accounted for as well. Most importantly, an accurate atmospheric model is used, specifically the Jacchia-Roberts model, upon which the NASA Goddard Trajectory Determination System is based, is used. The atmospheric model simulates seasonal and diurnal variations in density as well as daily variations in density due to solar and planetary geomagnetic activity. Past, current and predicted values for the appropriate solar and geomagnetic activity parameters are available from the United States National Oceanic and Atmospheric Administration (NOAA).

A nominal aerobrake shuttlecock angle of 25 degrees was selected and the variation of the resulting shape's drag coefficient with Knudsen number is incorporated into the simulation using custom plug-in scripts written in Matlab. The Knudsen number is continuously computed as shown below.

$$Kn = \lambda / D$$

Where,
λ = Mean free path of atmospheric molecules at current atmospheric density
D = Diameter of aerobrake

Other important parameters such as heat flux due to aerothermal heating (Figure 18) and aerodynamic loading (Figure 19) are also continuously computed using heat transfer and drag coefficients provided by LaRC. The aerodynamic loading is monitored to make sure it remains below safe limits. In the next phase of analysis, the heat flux due to sunlight and Earth albedo will also be computed so that this data may be combined with the aerothermal heating data and SPORT thermal properties in order to continuously estimate SPORT temperatures (Figure 20) such that they may also be monitored to make sure they remain within safe limits.

The natural lifetime of SPORT must also be continuously monitored. For a given combination of perigee & apogee (as influenced by lunisolar gravity and solar radiation pressure perturbations), ballistic coefficient and atmospheric conditions such as perigee on day or night side, solar max or solar min, the natural lifetime is pre-computed by batch-processing a large number of STK runs using Matlab as a front end through STK/Connect and the STK/Matlab Interface. The lifetime calculator and batch-processor are currently undergoing a significant upgrade in accuracy by switching from the STK Lifetime tool, which is designed for much longer-term propagations, to STK/Astrogator. Figure 21 shows the results of some early natural lifetime batch-computations.

In order to simulate the process of flying through safe perigee altitude corridors and periodically performing burns at apogee to maintain the limits imposed by the corridors an Autonomous Perigee Controller (APC) is implemented using advanced STK/Astrogator features such as constrained stopping conditions and multiply-nested control sequences including targeting segments. By propagating the trajectory using the APC, AeroAstro can estimate the required frequency and magnitude of perigee-correction burns at apogee. Thus, the required fuel-budget for the entire mission may be determined, which is a major factor in that it impacts the tank sizing and the volume and mass available for every other component. Figures 22 and 23 show some early results achieved in simulating trajectories and engine burns using the APC.

Preliminary steps have been taken towards incorporating operational uncertainties into the mission simulation. Operational uncertainties may arise from errors in orbit determination using GPS, from attitude uncertainties and the minimum impulse bit during engine firing, from orbit perturbations due to attitude control thruster firings (SPORT does not use pure couples), from uncertainties in solar and geomagnetic parameters and their affect on atmospheric density, as well as from other sources.
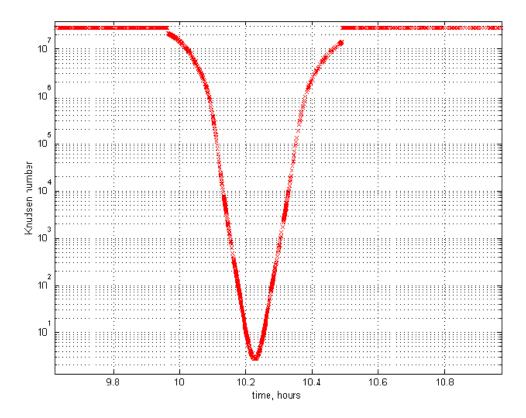
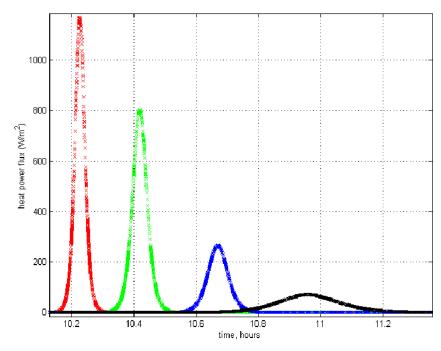**Figure 17. Knudsen Number Variation During an Early Pass**

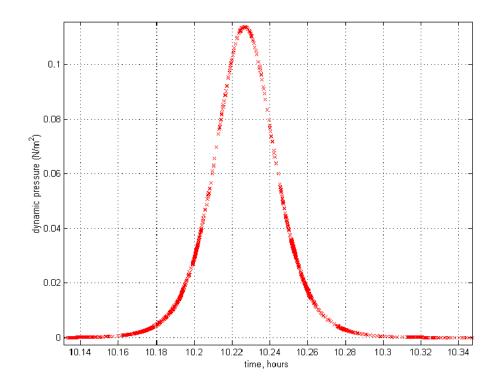**Figure 18. Variation of Heating Flux at Sample Passes During the Mission**

Figure 19. Dynamic Pressure Variation During an Early Pass
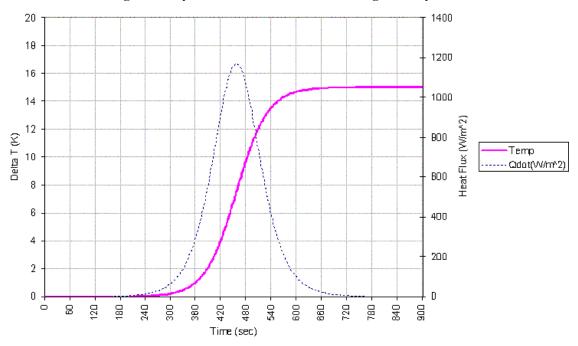

Figure 20. Estimated SPORT Temperature Increase Due to Aerothermal Heating
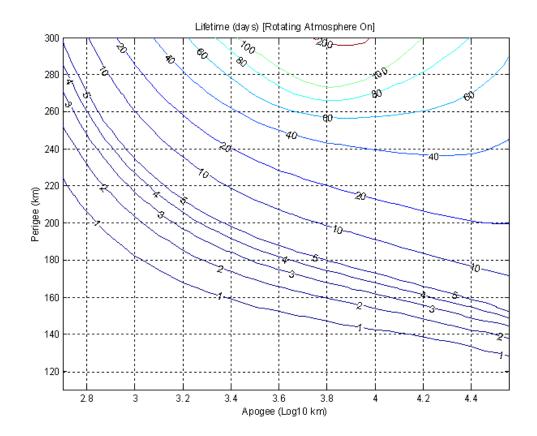
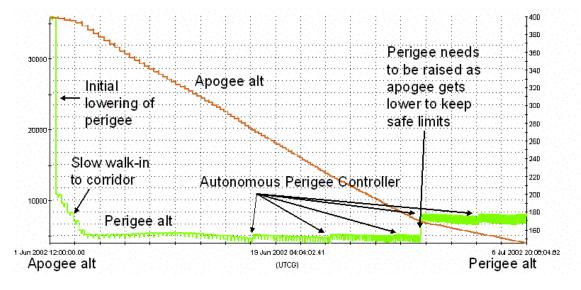**Figure 21. Estimated Lifetime of Unattended SPORT**
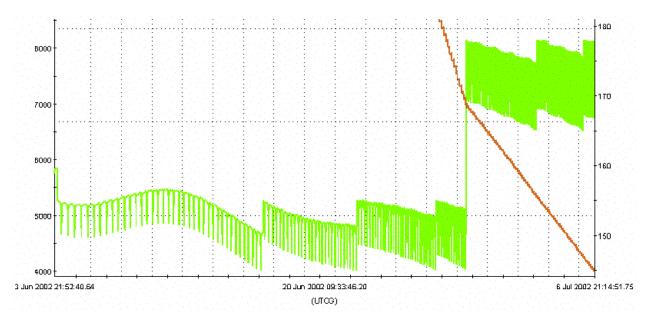

Figure 22. Time History of Sample SPORT Mission

Figure 23. Detail of Perigee Variation in Sample Mission Time History

Conclusions

As the SPORT aerobrake development progresses through the design phase into fabrication and test, and ultimately to flight demonstration, it will validate two key technologies needed in the commercial sector.

The first is the aerobraking technology itself. SPORT represents the first commercial aerobrake mission and opens the door for broad application of aerobraking technology. In addition to the regular commercial flights of SPORT in its payload transfer role, commercial aerobraking technology could be used by NASA or DoD for a wide range of future missions, ranging from planetary exploration to resupplying space assets.

Additionally, the commercial use of a large deployable structure on SPORT provides a foundation for further application of this technology. In addition to its use as an aerobrake, large deployable structures could be used for power generation, as a platform for thin-film solar cell technologies, and

reflectors to expand the power available to spacecraft. These structures could also be used as wake or sun shields, or even as communications or sensor arrays.

The SPORT aerobrake development represents a fusion of commercial, NASA and AFRL interests in a mutually beneficial program. Building upon NASA and AFRL developed technology, the SPORT aerobrake program provides an avenue to flight validate and commercialize key technologies, which then feeds additional technology back to NASA and AFRL for future use.

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