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Aerobraking to Lower Apogee in Earth Orbit with the Small Payload ORbit Transfer (SPORT™) Microsatellite Vehicle

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Abstract. AeroAstro, Inc. and Astronautic Technology Sdn. Bhd. (a Malaysian space company) are commercially developing the Small Payload ORbit Transfer (SPORT) vehicle, which uses advanced earth aerobraking technology to achieve efficient orbit transfer from Geosynchronous-Transfer Orbit (GTO) to Low Earth Orbit (LEO). After being delivered to GTO by a large launch vehicle, such as Ariane, SPORT uses its onboard propulsion system to adjust its perigee altitude to about 150 km. At this altitude, the large deployable aerobrake produces enough drag to reduce the apogee altitude from 36,000+ km to about 1,000 km in approximately 300 orbits. Upon reaching the target apogee altitude, the propulsion system is used to raise the perigee to the desired altitude, thereby allowing SPORT to release its payload.

Aerobraking technology enables orbit transfer in a cost-effective manner, reducing the overall mass of the spacecraft by drastically reducing the amount of propellant required to achieve the maneuver. The development of the SPORT aerobrake technology is discussed, along with a comparison of the SPORT aerobraking approach to NASA's successful aerobraking missions: Magellan and Mars Global Surveyor. The paper concludes with a discussion of the SPORT aerobrake details, including structural design, brake deployment, stability and control, and auxiliary features.

Access to Space

The primary hindrance to the widespread acceptance and use of microsatellites is the inability to obtain an inexpensive launch to an appropriate orbit. While some microsatellites make use of dedicated launches, the high cost of launching on existing small launch vehicles absorbs most the typical budget available for microspacecraft, leaving few resources available to meet the mission objectives.

With the absence of a near-term low-cost small launch vehicle, most microsatellite missions will continue to make use of the surplus launch capability of large launch vehicles as secondary payloads. While a small amount of surplus capability is available to polar orbit destinations, the vast majority of the surplus is destined for Geosynchronous Transfer Orbit (GTO).

GTO is an excellent orbit for large spacecraft ultimately bound for Geosynchronous orbit. However, most small spacecraft, due to their power, aperture, and communications constraints, the missions they tend to execute (remote sensing, space control, science, and technology demonstrations), and the limited number of radiation-hardened parts used, need to be in Low Earth Orbit (LEO).

The European Ariane 4 and 5 vehicles, which have standard secondary configurations for six microsatellites per launch, fully book their LEO launches for piggyback missions whenever they occur. However, their GTO launches, which form the majority of their missions, are rarely utilized by secondary payloads. There is little to no demand for microsatellite launches to GTO.

These GTO launches and their surplus mass capability represent an untapped resource, which could greatly assist the microspacecraft industry, if a method could be found to tap into it. After years of investigation, AeroAstro has developed a patented approach to offer this launch capability to the microspacecraft industry with its Small Payload ORbit Transfer (SPORT) product line. A conceptual drawing of SPORT is shown in Figure 1.

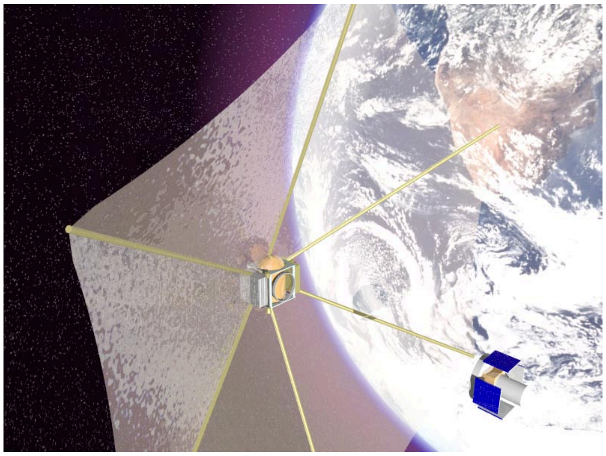

Figure 1 – Conceptual Drawing of SPORT

SPORT Product Approach

Since the Ariane launch vehicles routinely support secondary payloads and have numerous launches to GTO each year, Ariane was selected as the initial baseline launch vehicle for SPORT.

Three versions of the SPORT product line are currently in development by AeroAstro and Astronautic Technology Sdn. Bhd. (ATSB): Micro, Mini and Mini-XL. These versions correspond to similarly named secondary payload slots on the Ariane 5 launch vehicle. Table 1 lists the launch masses and nominal payload masses to 500 km circular altitude for the three versions of SPORT. The performance of SPORT to different altitudes is shown in Figure 2.

The SPORT product is designed with a modular architecture that allows for maximum commonality between versions. The core module of SPORT is the AeroAstro Bitsy™ kernel[*]. Bitsy includes the components that are often common to most satellites including power regulation and command and data handling. The SPORT Bitsy will include processing capability provided by the Bitsy-DX computer, a processor based on automotive technology.

Table 1 - SPORT Vehicles and Payload Masses

SPORT Vehicle Class	*Total Launch Mass (kg)*	*Nominal Payload Mass (kg)*
Micro	*120*	50
Mini	*300*	190
Mini-XL	*600*	370

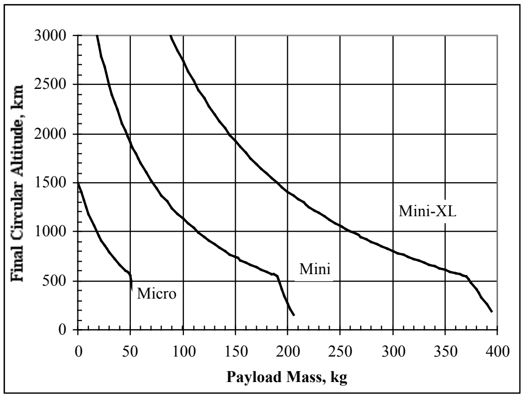

Figure 2 - SPORT Version Performance

After launch to GTO, SPORT will use a combination of aerobraking and propulsive maneuvers to transfer to LEO. With the SPORT/payload combination delivered successfully to the target LEO, SPORT will release the payload to begin its mission. A collision avoidance maneuver will occur immediately following payload release, with a burn-to-depletion maneuver used to assist the aerodynamic deorbiting of SPORT.

SPORT will also support a configuration called PASSPORT. In this configuration, SPORT remains with the payload after orbit transfer and provides bus type services to the payload. These services may include power, communications, processing, attitude determination and control, as well as station keeping.

Aerobraking Technology Development

Since a Hohmann transfer from GTO to LEO would require a total velocity change greater than 2,000 m/s, it is not practical to use conventional spacecraft

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[*] Bitsy is scheduled to be launched on the Shuttle in late 2001 as part of the SPASE mission.

propulsion technology to make this maneuver. However, aerobraking technology provides the means to greatly reduce the amount of ΔV that the propulsion system has to supply. By passing through the atmosphere, some of the spacecraft orbital energy can be transferred to the atmosphere. With aerobraking, the GTO to LEO ΔV can be reduced to a few hundred meters per second, which can be easily delivered with conventional monopropellant propulsion technology. With the benefits of aerobraking clearly established, several approaches to the technology were considered.

The first option considered was to fly SPORT with a low perigee altitude, in the range of 90 to 100 km, to lower the apogee in as few passes as possible. Several versions of this approach were considered, but the high heating environment and the need for active control to keep the heat shield in the correct orientation made the approach too risky. Since heating rate was equated to risk, the effort investigated several approaches with heating rates that were low enough to allow SPORT survival regardless of orientation and not require special thermal protection.

One of these approaches was to deploy an extremely large inflatable sphere and perform the aerobraking with a perigee in the range of 600 km, which is typical of Ariane GTO launches. However, it was determined that the sphere would have to be on the order of 500 meters diameter to meet the maximum mission duration goal of 90 days. While conceivable, the sphere would have to be built from amazingly thin material to be mass competitive with pure propulsion options, and so the approach was rejected.

With the very low and very high altitude approaches rejected, the effort focused on identifying an approach, which minimizes the aerothermal risk and maximizes the mass advantage, while meeting the under 90-day mission duration goal dictated by the market assessment. The first step in developing this approach was to identify a "safe" altitude for aerobraking. While it was found that under some circumstances SPORT could aerobrake under 130 km altitude, the large rate of change in density with altitude combined with atmospheric variability and altitude control limitations led to the establishment of 130 km altitude as the floor for SPORT aerobraking.

While aerobraking at or just above the 130-km altitude floor would allow the size of the aerobrake to be minimized, controlling the perigee to the necessary accuracy would be extremely difficult and propellant intensive. A build up of the perigee control errors showed that a perigee control accuracy of about ±5 deg was reasonable for a low cost spacecraft. Furthermore, it was found that the perigee altitude would drift over time due to a variety of sources including non-impulsive aerobraking, J2 and lunar effects.

These factors led to the establishment of an aerobraking flight window of 155 km ± 15 km for perigee. Within this aerobraking window, it was determined that the aerothermal loads would be sufficiently low to allow the use of conventional spacecraft materials. This window allows several aerobraking passes to occur between perigee adjustment maneuvers, which simplifies the mission operations and reduces system complexity. This mission feature also serves to reduce mission risk by eliminating the criticality of any given orbit adjustment maneuver and giving the operations team several days of margin.

With the aerobraking flight window established, the aerobrake was sized to provide a maximum transfer duration of 90 days regardless of atmospheric conditions. After several design iterations, it was determined that an aerobrake with a profile area of 0.25 m^2 per kilogram would be sufficient for an overall drag coefficient of 1.5. Within the free molecular flow regime, the pressure acting upon an inclined surface can be modeled using modified Newtonian mechanics. With this approach, the drag coefficient can be found from

$$C_D = Cp_{max} \sin^3\alpha \quad (1)$$

While Cp_{max} varies with Mach number and atmospheric properties, it can be assumed to be between 1.8 and 2.0 for SPORT. So with the aerobrake panels angled aft by 25 degrees, providing a nominal angle attack of 65 degrees, the SPORT drag coefficient can be estimated to be approximately 1.5. While this approximation was useful in the initial sizing and shaping of the aerobrake, more extensive analyses are necessary to characterize the SPORT aerodynamics.

With the basic shape, size and flight envelope determined for the SPORT aerobrake, see Figure 3, the baseline mission profile was established.

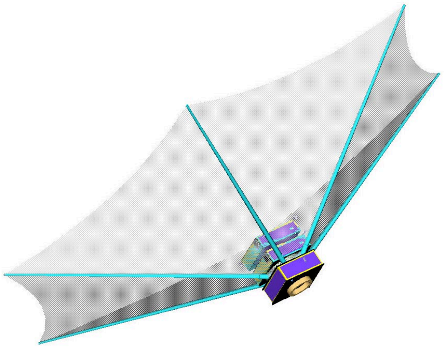

Figure 3 - SPORT Aerobrake Configuration

SPORT Mission Profile

The baseline SPORT mission is to launch into GTO and maneuver via Aerobraking to LEO. The different phases of the mission are shown in Figure 4 along with Table 2.

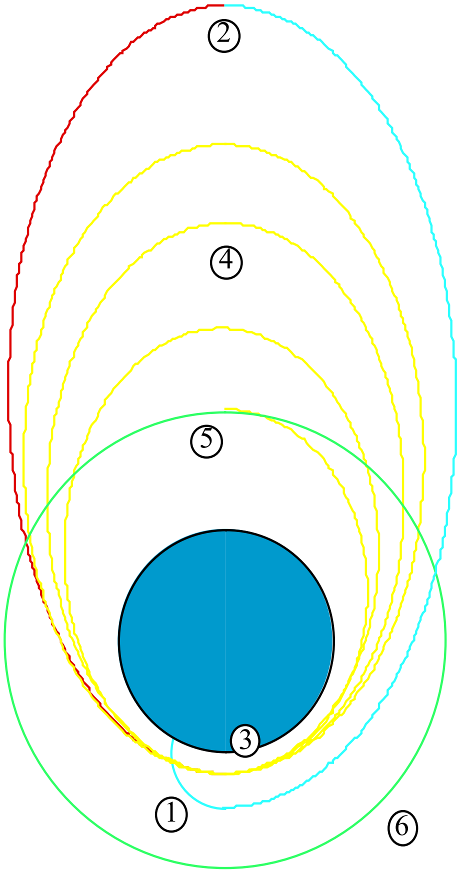

Figure 4 - SPORT Mission Profile

The initial GTO parameters are dictated by the launch vehicle. Some time after launch, SPORT lowers it's perigee, which initiates the Aerobraking phase of the mission. The lowering of the perigee from the initial 620 km to the 155 km aerobraking altitude will be performed in a series of burns to ensure that SPORT does not overshoot the window and penetrate too low into the atmosphere.

The Aerobraking phase lasts 60 +/-30 days – until the spacecraft apogee reaches the payload's final altitude. The mission duration is primarily determined by the atmospheric conditions at the time, with missions during solar max tending to be shorter and those during solar min longer. As the SPORT flight characteristics become known, mission control may be able to bias the aerobraking altitude to the upper or lower parts of the flight envelope to adjust the mission duration.

Table 2 - SPORT Mission Phases

Mission Phase	Action
1. Launch to GTO	• Systems checkout • Aerobrake deployment
2. Perigee lowering burn	• Lower perigee to target window
3. Aerobrake drag near perigee	• With each pass through the atmosphere, the aerobraking drag reduces the orbit energy and lowers the orbit apogee
4. Apogee burns to control perigee	• Apogee burns will be made as necessary to adjust perigee altitude to counter secular orbit disturbances and maintain perigee altitude within the target window
5. Perigee raising burns	• As the apogee altitude nears the desired level, several perigee burns will be made over several orbits to raise the perigee out of the atmosphere and thereby stop the aerobraking drag
6. Final circular orbit	• Perform thruster burns to trim out orbit parameters • Release payload
Post Mission	• Potential burn to depletion to promote the deorbit of the spent SPORT hardware

During the course of the aerobraking phase, various factors will cause the aerobraking altitude to drift. These factors include J2, lunar and non-impulsive effects. To counter this drift, it is expected that perigee trim maneuvers will be required on average once every three days. When the apogee has been reduced to its target altitude, the perigee will be raised to circularize the orbit. Following circularization and payload release, SPORT will perform collision avoidance and deorbit maneuvers.

Aerobraking Performance Comparison

When the SPORT mission profile is compared to the two NASA missions, which successfully used aerobraking, Magellan and Mars Global Surveyor (MGS), many similarities can be seen. As shown in Table 3, the dynamic pressure, aeroheating, Knudsen number, and flow regime for SPORT is similar to these missions. This similarity provides confidence that the mission can be accomplished with existing technology, and allows the design team to leverage the data generated from these missions to improve the SPORT design. In particular, the knowledge of aerodynamic and aerothermal loads aids in the selection of aerobrake structural materials and the establishment of reasonable design margins.

Table 3 - Aerobraking Parameters Comparison

	Magellan	MGS	SPORT
Dynamic Pressure, N/m^2			
Max	0.4	0.9	0.26
Avg	0.27	0.18	0.17
Aeroheating, W/cm^2	0.3	0.08	0.1
Knudsen #	3-12	0.3-3.0	3-14 * 1.3-6**
Flow Type	Free Mol	Trans.	Free Mol
Drag Coef.	2.2	1.9-2.2	~1.5
Mass, kg	1100	760	120 † 600 ††
Profile Area, m^2	23	17	30 † 150 ††
Ballistic Coef, kg/m^2	~22	~22	2
Avg ΔV per pass, m/s	1.65	1.37	76
Avg Apoapsis change, km/day	114	180	586

* Value for Micro-SPORT
** Value for Mini-XL-SPORT

However, this is where the similarities end. The mission of SPORT is to transfer a payload from GTO to LEO within a commercially viable period of less than 90 days. The combination of large total ΔV and short duration requires that SPORT be designed with a much lower $(^1/_{10})$ ballistic coefficient than the NASA missions. Since the mass and drag coefficient of SPORT are relatively fixed, SPORT achieves the low ballistic coefficient with an extremely large profile area compared to the spacecraft body size. When deployed, the SPORT aerobrake has a profile area about eighty times that of the stowed spacecraft.

This low ballistic coefficient will provide SPORT with the substantially greater deceleration per pass required by the market. Table 4 shows a comparison of the aerobraking performance of these three missions.

Aerostructure Configuration and Design

While both Magellan and Mars Global Surveyor used their flat solar panels and high gain antenna dishes to provide the profile area, the extremely large profile area and associated packaging factor required by SPORT do not allow this approach to be used. Instead, SPORT has to make use of a structure that is primarily an aerobrake and secondarily for power and communications.

Table 4 - Aerobraking Performance Comparison

	Magellan	MGS	SPORT
Aerobrake Periapsis, km	135-141	100-134	140-170
Avg Periapsis Density kg/km^3	8.3	19.4	3.2
Periapsis Speed, m/s			
Initial	8,570	4,810	10,284
Final	7,362	3,593	7,780
Total Δ	1,208	1,217	2,504
Apoapsis Alt, km			
Initial	8,470	54,028	35,883
Final	541	453	500
Total Δ	7,929	53,575	35,383
Aerobraking Duration, days	70	298	60 ± 30
Aerobraking Orbits	730	890	330

While a variety of aerobrake configurations could have been selected, secondary design factors, such as payload protection, thruster orientation and aerodynamic stability, were crucial. While potentially the lowest mass solution, the spherical aerobrake approach complicated the propulsive aspects of the mission and provided inadequate protection to the payload, so it was rejected. While structurally efficient, the toroidal and ballute approaches were not very efficient in providing profile area for the mass.

With the selection process narrowed to flat disk type aerobrakes, angled aft for aerodynamic stability, the examination focused on structural optimization. A variety of approaches were considered to deploy and hold the flat panels against the aerodynamic loads. Traditional folding panel approaches were ruled out due to their high mass and packaged volume, while centrifugally stiffened blades required excessively large spin rates to overcome the aerodynamic forces and moments.

After eliminating pyramidal truss structures for mass and complexity issues, a simple umbrella structure approach was selected. This approach consists of several radially oriented cantilevered booms that suspend thin brake panels between them. To provide the desired aerodynamic stability, the booms are angled 25 deg aft to produce a shuttlecock shape.

Several technologies were considered for the boom structure and aerobrake deployment. Of these, two stood out as promising. One approach was to use telescoping inflatable booms to deploy the aerobrake radially. The second approach was to spirally deploy the aerobrake with elastomechanical booms wrapped around a hub. Each of these options is described briefly below, with the flight approach to be selected in the near future.

For either of these options, the brake panels themselves would be similar. These brake panels would be fabricated from thin Kapton film. The panels are aluminized on each side and short circuited front-to-back to prevent charge build up and minimize static issues during deployment. The panels may have an additional white paint coating to protect them from atomic oxygen erosion and improve the thermal properties.

Inflatable Boom Approach

In the inflatable boom approach, each of the six aerobrake booms would consist of a tapering isogrid tube with an internal pressure bladder and an external solar shield. There are rings fixed to the boom at the tops of folds. The brake panels are attached to these rings. Figure 5 shows a sketch of a boom in its stowed configuration.

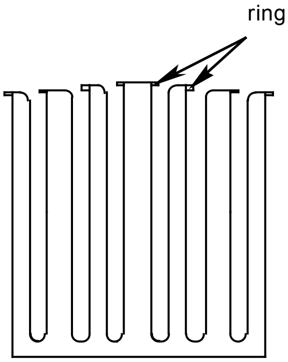

Figure 5 - Stowed Inflatable Boom

As pressure, is applied to the booms, the booms telescopically deploy and pull the aerobrake panels into place. Ground commands will control the deployment rate. All six booms will deploy simultaneously, starting with the base segments.

Once the booms are fully deployed, ground commands would start the rigidization process. UV lamps located at the base of the booms will direct UV light down the length of the booms. The light will serve as the catalyst to start the curing process of the UV sensitive epoxy.

With the booms fully deployed and rigidized, ground commands will command the valves to vent the pressure from the booms.

Elasto-Mechanical Boom Approach

In the elasto-mechanical boom approach, each of the six aerobrake booms would consist of a sparsely braided isogrid truss made from carbon or glass fibers. These booms would be designed to provide normal, torsional and bending stiffness per unit mass, while providing a low tangential stiffness to allow spiral packaging.

The booms and folded brake panels would be wrapped around a central hub and restrained with a strap. When commanded from the ground, this strap would be released. The elastic energy stored in the wrapped booms would then cause the booms and brake panels to unfurl. A sketch of a single boom deployment is shown in Figure 6.

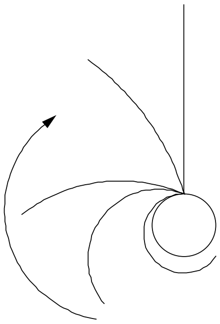

Figure 6 - Elastic Boom Deployment

While the spiral deployment of the aerobrake will impart angular momentum to the spacecraft, it will have a minimal impact on SPORT operations since SPORT will be in a free tumble mode during deployment. Since the deployment greatly increases the spacecraft inertia, the imparted spin rates will be small and easily eliminated when the attitude control system is engaged.

Aerodynamics and Stability

While the aerothermal environment is fairly benign within the SPORT aerobraking window, it was determined that shielding the payload from this environment would be favorably received in the market place. Since SPORT operates within the free molecular flow regime, the aerobrake makes a good shield so long as it remains between the flow and the payload.

It is possible to use active attitude control systems to maintain the proper orientation, but the aerodynamic moments and constantly changing angle of attack would require a system with a capability beyond that appropriate for a low cost microspacecraft. So it was determined that SPORT would be uncontrolled during the aerobraking phase and would rely upon aerodynamic stability to shield the payload.

This aerodynamic stability is achieved by angling the six aerobrake booms aft by 25 degrees. This configuration produces a six-sided pyramidal shape. Initial analyses show that this shuttlecock shape is statically and dynamically stable during aerobraking, and will turn to keep the SPORT body facing into the wind and thereby shielding the payload from the flow, see Figure 7.

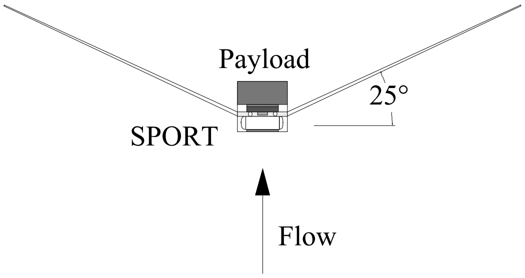

Figure 7 - SPORT Side View

Starting from a random orientation, SPORT will turn into the wind as the atmospheric density increases with decreasing altitude. As it passes through the most severe portion of the aerobraking phase, around perigee, SPORT will oscillate around a zero degree angle of attack depending upon the damping, which can be achieved. However, as SPORT exits the atmosphere, the rapid reduction in atmospheric density will leave SPORT with a residual amount of angular momentum.

While the resulting angular rate will be small, the cumulative effect over several aerobraking passes will put SPORT into a tumble and hence produce the random initial orientation. Initial analyses have shown that these rates are self-limiting, which will allow SPORT to remain uncontrolled for long periods of time. This capability greatly simplifies the mission operations during the 60 ± 30 day mission.

Auxiliary Features

The SPORT Aerobrake is a very large structure that will shadow the SPORT body in most orientations. This shadowing limits the effectiveness of body mounted solar arrays and prevents their use as the primary power supply for SPORT. To overcome this, solar arrays will be mounted on the aerobrake panels.

The primary power for SPORT will be delivered by six solar array panels mounted on the aerobrake surface; three on the front and three on the back. In addition to these large panels, four secondary panels will be mounted on the body of SPORT to provide some power when the aerobrake is stowed.

While most spacecraft tend to use high performance solar cells in their arrays, several factors make this unnecessary and impractical for the primary solar arrays on SPORT. The flexible nature of the aerobrake and its high packaging factor when stowed led the design team to investigate flexible solar array options. Various flexible solar cell materials are available, but they tend to have much lower efficiencies, 6-10% for flexible materials compared to 16-28% for rigid materials. Though with the large surface area available on the aerobrake, the low efficiency was not an issue. With the short mission life eliminating the need for cover glass, the flexible solar arrays provide SPORT with a better specific power (W/kg) than which could be obtained with rigid panels.

However, the secondary arrays do incorporate high performance cells due to the limited surface area available on the SPORT body. These arrays make use of triple junction Gallium Arsenide cells.

Since the aerobrake acts as a radio shield as well as a sun shield, it was determined that SPORT would need antennae mounted on the aerobrake in addition to body mounted antennae. With an antenna mounted at the tip of two booms, SPORT can achieve omni-directional antenna coverage. The body-mounted antenna provides the communications capability before the aerobrake is deployed.

Conclusions

While somewhat exotic, aerobraking represents a technology with the potential to enable a dramatic growth in the micro- and small-satellite industry. To access this potential, AeroAstro and ATSB have applied aerobraking technology in the innovative SPORT product line.

While still relatively new, AeroAstro and ATSB's aerobraking technology has been extensively investigated and is mature enough for near-term flight operation. SPORT's use of aerobraking is similar to NASA's successful aerobraking missions, Magellan and Mars Global Surveyor. This provides a level of confidence that aerobraking can be successfully applied to an Earth centered mission.

With aerobraking technology, AeroAstro and ATSB will provide the small satellite industry with an affordable avenue to space. This capability should enhance the overall acceptability of micro- and small-spacecraft solutions in future missions.