AIAA-LA Section/SSTC 2003-4002

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W. Paul Blase, Charles F. Radley
TransOrbital, Inc.

1st Responsive Space Conference
April 1–3, 2003
Redondo Beach, CA

AIAA-LA Section/SSTC 2003-4002

THE TRAILBLAZER^{TM} CLASS OF LOW COST SPACE VEHICLE

By W. Paul Blase and Charles F. Radley
TransOrbital, Inc.,
Alexandria, Virginia, U.S.A.

ABSTRACT

The concept of responsive space has many overlapping aspects. Military requirements to obtain tactical data rapidly or to reconstitute a decimated on-orbit constellation represent one class of drivers for responsiveness. Another class is represented by commercial news broadcast requirements to obtain satellite imagery of areas struck by a major natural disaster or in a state of war. Finally, there are many scientific phenomena that are either short term or that occur with little advance warning which could benefit from a rapid response capability. Two components at the core of providing the rapid response capability are launch vehicles that are launch-on-demand and spacecraft that are rapidly reconfigurable to match mission requirements. This paper addresses the latter: a spacecraft bus originally designed for the first commercial mission to the Moon that is reconfigurable and able to host various payloads that can support a wide range of missions.

The *TrailBlazer*^{TM} spacecraft is a 90-cm diameter, 85-cm tall three-axis stabilized 8-sided prism with photovoltaic cells on each face to provide power independent of orientation. The symmetric design was chosen to reduce the risk of mechanical failure associated with gimbaled sensors, antennas or solar panels, and to reduce spacecraft mass. The tradeoff is the necessity to reorient the spacecraft for sensor pointing and to orient the antenna for data transmission.

A number of factors can be adjusted to handle a wide range of missions. Although the surface area available for the solar cells is fixed, the type of solar cells can be varied from standard space-qualified silicon cells to high performance gallium arsenide cells, providing additional power depending upon payload power requirements. Similarly, as a function of mission duration and the associated radiation environment, a range of available off-the-shelf spacecraft control units, communications systems, and sensors have been identified that can be installed rapidly as required. Thus, it will not be necessary to have completely built up spacecraft in inventory. Rather, basic buses can be kept in inventory, along with various "plug-and-play" modules that can be installed rapidly, keeping costs down. In addition, the bus can be mated with a range of kick stages to give it a broad range of orbit capabilities: LEO, MEO, GEO, or lunar. Various combinations of optical sensors are possible, including dual high or low-resolution visible sensors, one high and one low-resolution visible sensor, or combinations of visible, infrared and ultraviolet sensors.

Because of its small size, the *TrailBlazer*^{TM} spacecraft is also easily adaptable to a wide range of launch vehicles, so that if one is not available to accommodate a rapid response, the spacecraft could be mated rapidly to another launch vehicle. *Trailblazer*'s small size also allows it to be easily transportable from one candidate launch site to another.

The *TrailBlazer*™ thus represents a leap forward in defining the equation for combining rapid response, versatility, and low cost into a single entity to fulfill the needs of both commercial and military customers

Part 1 Description and Significance of the Spacecraft Architecture

TransOrbital proposes a standardized, modular architecture for microspacecraft that consists of a base bus module; a series of common modular attachments for power, propulsion, and other general-purpose spacecraft functions; and a standardized attachment, packaging, and interconnection format for payload modules. These modules may be manufactured and stored in an integration facility and then rapidly integrated in order to accomplish a specific mission. Beyond enabling rapid assembly and launch of a spacecraft, a standardized set of modules will enable significant reductions in the costs of launching conventional scientific, commercial, and government missions. A great deal of the expense involved in planning a mission lies in designing and testing the bus which supports the payload in orbit. A set of pre-tested bus modules is analogous to the truck chasses available from Ford or Chrysler, with the same basic chassis serving as the basis for everything from utility service trucks to plumber's vans. Because all but some special-purpose payload modules are common between spacecraft they may be pre-tested, thus greatly improving reliability. Also, because of the standardized data and power interconnection scheme, the requirements for spacecraft testing are kept to a minimum.

1.1 Microspacecraft and modular spacecraft.

Microsatellites (50 to 100 kg in mass) have been used for university and amateur radio satellite programs for quite some time. Larger satellites have greater equipment capacity and capabilities such as orbital maneuvering; however, microsatellites have the advantages of relatively low cost, rapid development, and a much wider variety of launch options. Given recent advances in microelectronics, micromachining, software, and systems integration, microspacecraft are now capable of performing tasks that make them attractive for flexible space science missions as well as DoD and other national security missions. Recently, several military programs have explored the concept of replacing large satellites with clusters of smaller microspacecraft flying in formations tens of meters to kilometers across, acting cooperatively. The DoD is also investigating rapid-response Single- and Double-State-To-Orbit launch vehicles that can put up to 100 kg into Low-Earth-Orbit on very short notice.[i]

Several modular spacecraft buses are in use for larger spacecraft, most notably the Fairchild Multi-Mission Modular Spacecraft used for several missions, including Solar Maximum and Topex/Posiedon.[ii] Several small satellite companies have recently begun work on modular microspacecraft. One notable example is the SpaceFrame, a "plug-and-play" modular bus created by AeroAstro.[iii]

1.2 TrailBlazer

TransOrbital , Inc., Alexandria, Virginia, is developing the *TrailBlazer* lunar imaging mission, depicted in Figure 1 and described further in Part 5. *TrailBlazer* is a 3-axis stabilized bus that will carry 2 high-definition cameras into lunar orbit to take images of the lunar surface and environs. The trans-lunar trajectory burn is accomplished by a solid-rocket booster, shown in Figure 1; once at the Moon, all other orbital maneuvering and attitude control is accomplished using an monopropellant (H2O2) thrusters. The spacecraft also carries a full complement of attitude sensors, including sun and horizon sensors and a fiber-optic inertial measurement unit.

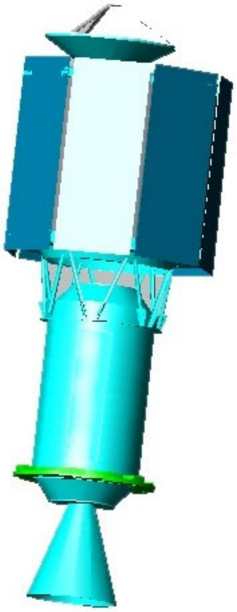

Figure 1 - TrailBlazer lunar spacecraft (with solid TLI booster)

In order to minimize the cost of the spacecraft bus, and to maximize its usefulness for follow-on missions, *TrailBlazer* is designed in a modular fashion, as shown in Figure 3. The flight computers, attitude control sensors, telemetry transceiver, power storage and handling, and all other "bus" functions are concentrated on the rear bulkhead, around the hole for the thruster nozzle. The propulsion system – which takes up the majority of the volume of the spacecraft, is centrally located. The payload cameras and the high-gain antenna are located at the front bulkhead.

At the time of this writing, *TrailBlazer* is in the final design phase, with construction of some subassemblies begun. Launch is scheduled for the end of 2003, using the Russian *Dnepr* launch vehicle produced by ISC Kosmotras.

1.3 Modular Spacecraft Architecture

TransOrbital will leverage off of the *TrailBlazer* design and develop a modular micro-spacecraft bus architecture, suitable for a variety of current and proposed launch vehicles and for government, educational, and commercial customers. The architecture will be designed to facilitate rapid integration and checkout of a spacecraft so as to enable missions with minimal notice, and also to minimize the cost of assembling a bus for a particular payload. The proposed architecture is particularly suitable for several proposed rapid-response launch vehicles with small payload capabilities, on the order of 100 kg.

Part 2 Development Approach

2.1 Modular Architecture

For the proposed modular architecture, TransOrbital proposes to leverage the *TrailBlazer* design and develop an architecture as illustrated in Figure 2.

The basic bus functions are concentrated in a flat "pizza box" module that forms the base of the spacecraft. These include:

- The flight control computers

- Attitude control and navigation sensors (e.g. optical sun and horizon sensors and the IMU)
- Attitude control systems (e.g. thrusters and/or reaction wheels)
- Data handling computers
- Telemetry transceivers and antennae
- Power storage and handling.
- Sufficient photovoltaic capability to maintain the base spacecraft, primarily for emergency and long-term on-orbit storage purposes.

The base module forms a complete spacecraft, albeit one with minimal mission capability. Depending on the mission, a number of support modules bolt onto its front and rear faces to support the requirements of a particular mission and payload. Onto the rear face fit orbital maneuvering/adjustment modules. These could include gravity-stabilization tethers or booms, electrodynamic tethers for raising or lowering the spacecraft's orbit or mono- or bi-propellant thrusters.

Onto the front plate go the payload and additional power-supply modules as required. The figure shows a few possibilities: Large payload modules are fastened directly to the bus faceplate. For payloads that require 100 to 200 Watts of power, and do not require side-facing access to space, a set of wrap-around photovoltaic (PV) panels forming a shroud around the payload could be used. For multiple payloads, a "backbone" module could be used, with a vertical strut onto which modular payload "blocks" could be mounted. Depending on the power requirements, the wrap-around PV shroud could again be used, or a module with deployable photovoltaic panels or other power source inserted. Additional modules not shown could include communications modules, with high-gain antennae and high-bit-rate transmitters or even laser communications station and mechanical modules with, for instance, grapple targets for use with the manipulator arms used on the Shuttle and the ISS.

One significant advantage that must be mentioned with respect to a modular architecture such as described is that all of the modules and interfaces can be extensively tested and validated prior to use. So long as the payload module conforms to the interface specifications, unforeseen interactions will be kept to a minimum.

2.2 Modularization Technologies

In order to make such a modularized approach possible, four things must be standardized: the mechanical envelope, the mechanical/thermal interface, the power supply connections, and the data buses.

Defining the physical envelope and the mechanical/thermal interface will primarily be a matter of investigating the anticipated payloads and arriving at a structure that can hold them securely during launch and in orbit, while also allowing for rapid and standardized connections. Included in this part of the definition is the mechanism that will stabilize the temperature of the payload within acceptable margins. To some extent this will be accomplished through proper insulation and heater usage; for high-power payloads, it will be necessary to define a method for dynamically extracting heat to heat-sinks located on the base bus module. The payload module envelope will be a balance between the volume required for the spacecraft bus components, the volume required for the payload elements, and the volume allowed by the launch vehicle.

Fortunately, a considerable amount of work has been done on the two latter items, and defining these elements of the architecture will primarily be a matter of choosing from the available standards. Using available standards will yield significant cost and time savings, primarily because components may be purchased off-the-shelf and in larger lot quantities. Regarding power, simply due to the availability of existing components we recommend using the 28VDC standard avionics voltage, although further investigation may indicate the use of other voltages.

The data buses fall into two categories: lower bit-rate – less than 1 Mbit/sec - buses used to transmit commands and telemetry between spacecraft components, and high-rate buses used to take data from sensors to processors and the communications subsystem.

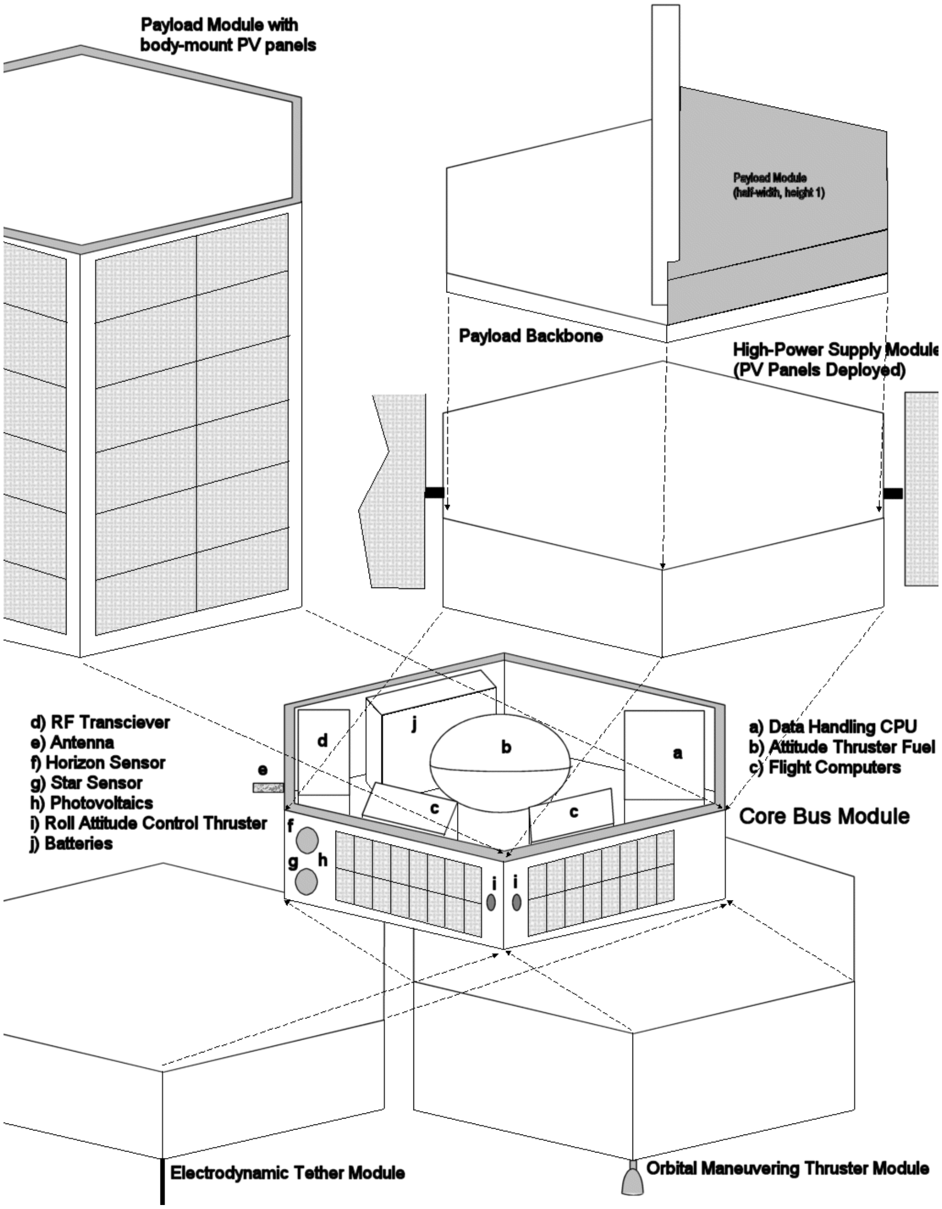

Figure 2 - Proposed Modular Architecture

Generally, serial buses are recommended for component interconnection due to the ease of interconnection and the lower wiring costs. Parallel buses, such as PCI, can be used within a module, e.g. as the backplane for the flight-control or data handling computers, but that is outside of the scope of this definition. Two existing standards that can be utilized are SpaceWire, a variant on IEEE 1355 and LVDS that can handle up to 100 Mbit/second, and the Fiber-Optic data bus, which will handle up to 1 Gbit/second. Other possibilities include the MIL-STD-1553 serial data bus which, although old, is still in widespread use. It is also interesting to note that the CAN bus[1] (Controller Area Network, ISO 11898, originally created for automotive applications) has been implemented in several European spacecraft applications, including the ESA SMART mission. Using a commercial data bus produces great cost savings through the use of commercial off-the-shelf components.

The payload modules are defined as a series of blocks that fasten onto either the base module or the backbone through the use of standardized electrical and mechanical connections. In a manner similar to the shipping containers used to transport cargo, or the standardized electronics equipment racks, larger modules are sized as multiples of smaller ones, so that they easily stack on top of the base spacecraft module. Assuming the hexagonal shape shown in Figure 2, the smallest module might be sized as a half of a hexagonal slice, say 5 cm thick. Two of these then fit together to form a full-sized module of height 1. Larger modules could be of multiples of height 1 as required, either a half-width or full width.

Just as important as the mechanical standardization is the software standardization. Standard data transfer formats and command procedures should be defined for all modules so that they are “plug-and-play” to the greatest degree possible. As with the data buses, there are available standards that should be examined for use, especially the CCSDS (Consultative Committee for Space Data Systems) standards.

2.3 Systems Miniaturization

In order to maximize the available payload mass and volume, the standard bus “overhead” must be kept as small and light as possible. Of course, there is a tradeoff between miniaturization and cost, especially in a space environment, and a significant part of the preliminary study will be the determination of the tradeoffs involved. Also, there is already a considerable amount of work being done on many spacecraft components and systems, by private companies, by NASA, and by the DoD. Therefore, another large part of the architecture development will be to investigate the ongoing work and choose the elements that will be of greatest benefit.

TransOrbital investigated a number of existing “standard” spacecraft buses available on the market. None of these are directly suitable for use with this architecture, but examination does indicate which systems could most benefit from aggressive miniaturization. In order of descending importance, these include:

a) Power generation, storage, and management subsystems. Figure 3 shows a comparison of the dry (unfueled) bus mass (not including payload subsystems) vs the ratio of the power available to the bus mass for the spacecraft examined during the preliminary study. It is interesting to note that most of the spacecraft have a ratio of less than 1 W/kg. Given the desired payload of

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[1] CANbus is a trademark of Robert Bosch

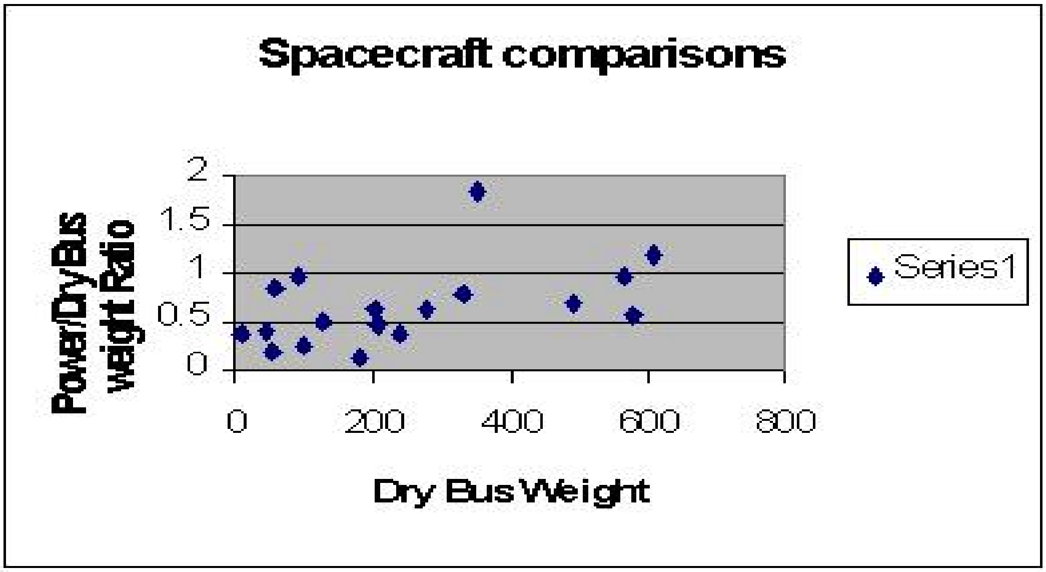

Figure 3 - Spacecraft Comparison, bus mass (kg) vs power/mass ratio (W/kg)

100 kg, the bus should have a mass of less than 50 kg, preferably less than 20 kg. A power/mass ratio of 1 W/kg yields little power to drive the payload. One of the most massive subsystems on LEO spacecraft is the power storage used, typically NiCd or NiH batteries. Some significant benefits could be obtained from aggressively pursuing alternative rechargeable energy storage. For instance, several efforts are currently investigating the use of flywheels as energy storage in spacecraft. These save additional mass by doubling as reaction wheels for attitude control. Even more benefits would be gained by pursuing power generation technologies and increasing the efficiency of solar energy collectors, both photovoltaic and thermovoltaic. Nuclear systems are not considered here, primarily for political reasons, although they could be considered in the future. For primary power, triple-junction GaAs photovoltaics are currently the best power/mass performers, but other technologies with even better outputs are being developed.

b) Thermal control subsystem. Currently, most spacecraft rely on relatively heavy insulation and heat conduction plates to control the temperatures of internal components. On the one hand, heat from the electronics on-board must be removed, on the other the thermal radiation from the Sun must be avoided. While insulation technologies are probably about as good as they are going to get, benefit could be gained from active heat transfer, most likely by circulation of working fluid between the heat source and the heat dump. Additionally, work is being done at NASA and various DoD agencies on micro-mechanical and thermionic coolers that can actively transfer heat from a load.

c) Propulsion systems. Propellant for orbital maneuvering and maintenance is a major mass element, although there are additional factors of stability and handling safety that must also be kept in mind. The use of electric rockets, such as plasma or Hall effect thrusters, maximizes the available reaction mass, although thrust tends to be low and they put an additional drain on the power system. In situations where higher thrust levels and low cost are more important than mission duration, the recent development of propane cold-gas thruster by Surrey in the U.K. and pumped hydrogen peroxide (H2O2) systems by Laurence Livermore National Laboratory are of particular interest. One interesting possibility that could be explored is to combine the two, using the propane gas alone for attitude control, using the H2O2 alone for low-thrust propulsion, and injecting the propane into the H2O2 thrusters in a bipropellant mode where higher thrust levels are required. Using either electric thrusters or such propellants as propane and H2O2 have an additional benefit for the proposed modular bus: they are inexpensive, are not toxic or carcinogenic, and can be stored for long periods of time. This, in turn, means that the propellants can be kept in the same facility as the modules, possibly pre-loaded, greatly reducing the time required to prepare the spacecraft for launch.

d) Spacecraft electronics, including the flight computers and the RF subsystem. The mass here is not so much the electronics per se, but rather the circuit boards and mechanical chasses that hold them. Typically, since spacecraft electronics must be conduction cooled, heavy copper or other metal sheets are used to remove heat from the electronics. Replacing these with circulating fluids could save considerable mass.

e) Spacecraft structural elements and mechanisms. While the use of composite materials has reduced spacecraft mass considerably, a major component in spacecraft mass is still the photovoltaic panels, which must usually include the mass of a deployment mechanism and must take into account the requirement to remove heat from the cells. There is considerable work being performed on flexible cells that can be deployed using inflatable structures, and on the use of working fluids to remove the heat from the solar cells without needing a rigid metal back plate. Additionally, there are other power generation technologies that can be looked at, such as thermo-voltaic systems, that are more mass-efficient than photo-voltaic systems.

Part 3 Potential Applications

3.1 Potential NASA Applications

This research plays directly into the NASA space science technology development program by accelerating mission development times. For example, the Discovery and Explorer programs could realize significant cost saving by using the proposed technologies. There are many missions currently in the NASA planning process that are candidates for application of this technology.

. The modular architecture will permit flexibility of mission planning, allowing flight experiments to be changed late in the integration flow, hence the experiments will not need to spend long periods of time (sometimes many months) in the launch site ground processing flow. It will also facilitate flights at short notice to targets of opportunity, such as a newly discovered asteroid or comet making a close approach to Earth.

3.2 Potential Non-NASA Commercial Applications

This architecture is applicable to a number of possible government and private missions, both in Low Earth Orbit and in Earth-Moon space.

At this time, TransOrbital performs design and analysis, software development, and final integration in-house; component fabrication is accomplished through subcontractors. This will change as we grow following the *TrailBlazer* mission and acquire facilities. The best initial approach will probably be to license the architecture out for other spacecraft manufacturers to use in supporting their existing customers. Indeed, it might be best to offer the architecture as a public standard through an international organization like the AIAA (American Institute of Aeronautics and Astronautics) or the IEEE (Institute of Electrical and Electronics Engineers). This will help assure the widespread acceptance of the architecture and its use by customers.

Part 4 Summary and Conclusions

A rapidly configurable spacecraft constructed with proven, standardized interfaces and modules will yield significant cost savings over multiple missions. TransOrbital proposes such an architecture based on its *TrailBlazer* lunar imaging probe: a standard bus module with add-on payload, power, and propulsion modules that assemble to form a complete spacecraft. This architecture will also yield a significant increase in the number of missions that could be launched per year by reducing the time required to design and test the spacecraft. With an inventory of modules kept on-hand, this architecture would enable very rapid-response, even same-day, deployment-on-demand launches.

References

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[i] *Responsive Access, Small Cargo, & Affordable Launch (RASCAL) Demonstration Program, Phase I Program Solicitation 02-02*, December 10, 2001, DARPA/TTO.

[ii] Masaharu Suzuki, “Topex/Poseidon,” http://www.tsgc.utexas.edu/spaceraft/topex/index.html, University of Texas at Austin, 1999.

[iii] Jon Miller, Jim Guerrero, David GoldStein, Tony Robinson, “SpaceFrame: Modular Spacecraft Building Blocks for Plug and Play Spacecraft,” http://www.aria.seas.wustl.edu/ssc02/papers/iii-8.pdf, 16th Annual AIAA/USU Conference on Small Satellites, 2002.