SHERPA: A Flexible, Modular Spacecraft for Orbit Transfer and On-Orbit Operations

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Abstract. The Department of Defense Space Test Program is responsible for launching small experimental payloads and demonstration technologies as directed by the Space Experiments Review Board (SERB). The SHuttle Expendable Rocket for Payload Augmentation (SHERPA) program will develop a highly functional space vehicle – with several variants – that incorporates a scaleable, modular architecture to support a wide variety of missions, technologies, and configurations. The initial application of SHERPA will be as an orbit transfer vehicle designed to raise a payload from a low Space Transportation System (STS) flight altitude to an orbit with a nominal one-year lifetime. This capability will allow STP to take advantage of the low-cost Space Shuttle launch services and still achieve the mission lifetimes required for experiments.

In this paper, analysis and design of the SHERPA scalable, modular architecture will be discussed. In addition, applicable requirements and constraints levied upon the design by the customer, secondary payload deployment mechanisms, such as the Canister for All Payload Ejections (CAPE), STS safety, the concept of operations, and envisioned applications, will be addressed.

Introduction

Through a collaborative effort between the Department of Defense (DoD) Space Test Program (STP), Missile Defense Agency (MDA), the Air Force Research Laboratory (AFRL), and commercial partners, the SHuttle Expendable Rocket for Payload Augmentation (SHERPA) program team has identified an approach that will serve a dual purpose by taking a step towards on-orbit servicing capability and addressing a near-term need for an orbit-transfer capability from the Space Transportation System (STS). By combining a set of new technologies with systems already under development, an STS-based orbit transfer vehicle is being developed that will validate several key technologies needed for both on-orbit servicing and asset re-tasking missions of the future.

SHERPA will be a highly functional vehicle – with several variants – that will nominally enable the delivery of payloads to any desired orbit within a 352 to 704 km altitude. The design will be fully extensible to future servicing spacecraft manifested on most available US launch vehicles. By leveraging the capabilities of SHERPA and current programs, such as Orbital Express and XSS-11, future civil and government efforts will be able to ultimately realize the ability to extend the operational lifetime – and value – of space assets and infrastructure.

The central SHERPA design incorporates a scaleable, modular architecture that is capable of supporting a wide variety of missions, technologies and configurations. The initial application of SHERPA is as an orbit transfer vehicle designed to raise a payload from a low STS altitude to an orbit with a long lifetime. Launched aboard STS using the Canister for All Payload Ejections (CAPE) secondary payload carrier, SHERPA will be capable of delivering a payload of 125 kg from a 352 km to a 704 km circular orbit. In addition to having several STS-based versions, SHERPA will be capable of being manifested on other launch vehicles, including the Delta IV and Atlas V Evolved Expendable Launch Vehicles (EELVs). The successful development of SHERPA will provide a core suite of technologies, components and a system architecture that can be applied to a wide range of missions, including future servicing missions.

This paper will address the SHERPA scalable, modular architecture, including applicable requirements and constraints levied upon the design by the launch vehicle, the concept of operations, applicable analysis and design, features and configuration of subsystems, and envisioned current and future applications.

Mission Requirements

Launch Requirements and Constraints

STP has a requirement to manifest secondary payloads on Space Shuttle missions. SHERPA will address the long-term needs of future missions by developing a vehicle architecture that first complies with the conservative system safety requirements of STS, assuring compatibility with all acceptance standards for manifest on other LV options. SHERPA will utilize CAPE to support the STP mission.

CAPE Design

The CAPE canister is an aluminum tube that provides the primary structural interface between the SHERPA stack and the STS sidewall (see Figure 1, left). The container features access ports on the End Cap and the Lid for ground access and safety verifications during processing of payloads.

SHERPA will utilize the additional Internal Container Unit (ICU) to further isolate the stack from the Shuttle. The ICU is a payload interface mechanism that serves as the unique payload carrier totally enveloping the payload. The ICU-to-CAPE interface will be the primary separation system for ejecting the ICU from the CAPE Canister. The payload geometry will control the ICU interfaces with the payload, with only the size and lid interfaces controlled by CAPE Canister inner dimensions. The CAPE Payload Envelope is 21 inches in diameter and 53 inches long. The entire volume is for payload use, without affecting the ejection parameters of the CAPE System (see Figure 1, right).

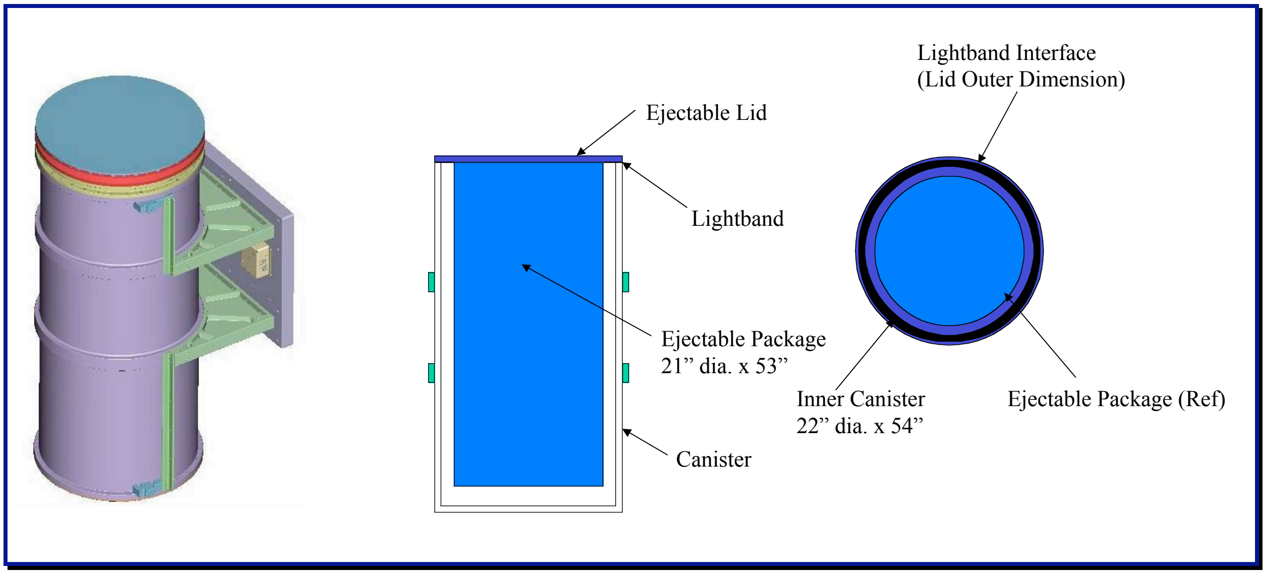

Figure 1. CAPE Mounting (left) and Canister Payload Envelope (right).

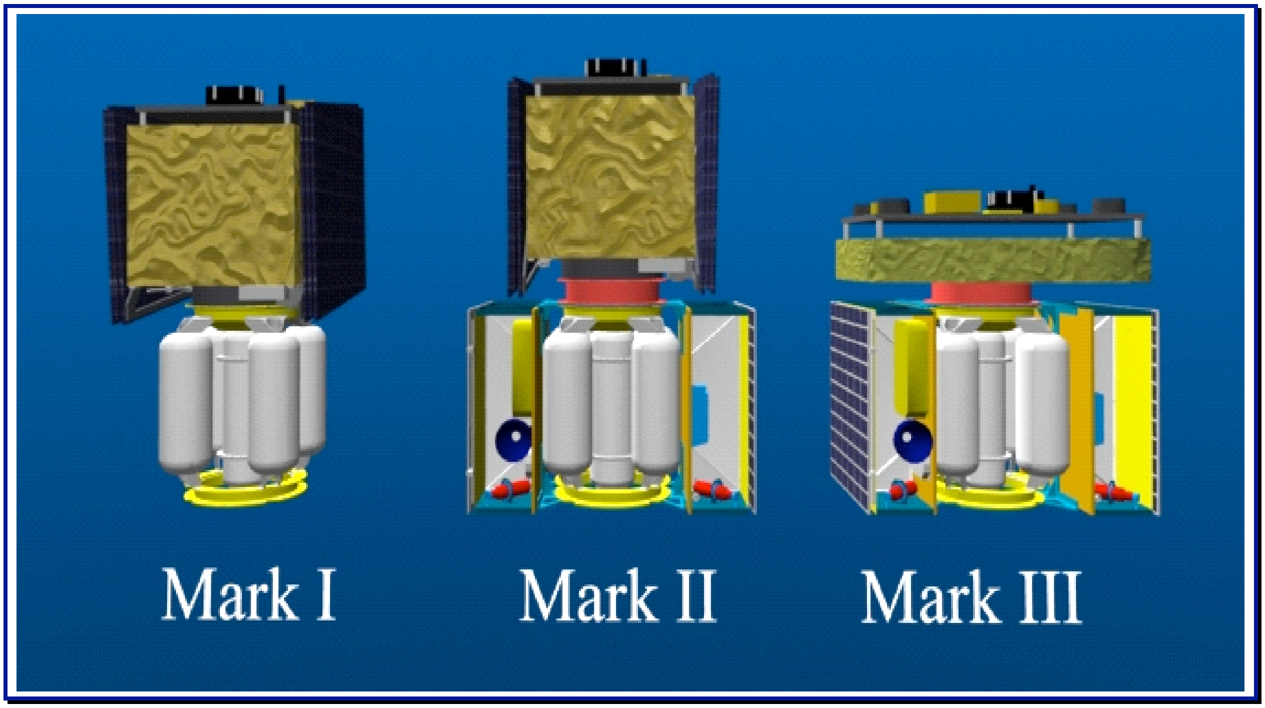

Figure 2. SHERPA Configurations.

SHERPA Configurations

As shown in Figure 2, the SHERPA orbital transfer system can be configured in three ways, increasing responsiveness and flexibility.

MARK I

The Mark-One (Mark I) SHERPA is the simplest configuration and utilizes only a propulsion module (PM). This configuration could be used to augment existing satellite systems, providing an auxiliary orbit adjust capability for satellites containing all other subsystems.

MARK II

The Mark-Two (Mark II) SHERPA is the program's baseline configuration and is ideally suited for the transfer and delivery of payloads to alternate orbits. The SHERPA vehicle features a wholly self-contained design architecture that operates independent of the subsystems of a host payload. Depending on the mission requirements, the SHERPA Mark II could be configured with either a Hybrid or Electric Propulsion Module. In addition, the design could also feature deployable panels and/or booms, depending on the needs of the mission. Following delivery of the payload to the target orbit, the Mark II would separate and de-orbit.

MARK III

The Mark-Three (Mark III) SHERPA will effectively provide a host payload with the orbit transfer capability of the Mark II, as well as a complete spacecraft bus capable of long-duration operations of up to one year. This configuration will serve as a platform for various space experiments and will utilize either the hybrid or electric PM for orbit transfer and stationkeeping activities. The Mark III will maximize flexibility and responsiveness by enabling use of a host of different spacecraft components and sensor systems depending on mission requirements.

Mission Sequence for the Mark II Hybrid

The primary requirement for a logistics servicing mission is the orbit transfer to the target space asset following separation from the launch vehicle (LV). To achieve this, the service vehicle must be able to stabilize itself from any induced tumble condition, orient itself in inertial space, establish a communications link with the mission operations center, either self-determine or receive ground-uploaded sequence commands. Ultimately, to enact the orbit maneuvers necessary for transfer to the desired final orbit position.

The following is the high-level mission sequence for the SHERPA Mark II Hybrid configuration:

- Launch on STS
- Stowed in CAPE, un-powered while STS performs primary mission
- CAPE deployment from STS
- Loiter on orbit, un-powered while STS is in vicinity
- Power-up and system checkout, with propulsion inhibits still in place
- Stabilize platform, acquire initial attitude, update gyro biases
- Obtain ground-commanded clearance for translation maneuver after re-entry of STS and sufficient separation from ISS
- Perform Hohmann Transfer
- Separate the payload from the SHERPA
- Perform Collision Clearance Avoidance Maneuver (CCAM) commands
- Execute end-of-life commands

Subsystem Design

The following sections describe the primary components and modules of the SHERPA architecture.

SHERPA Avionics

AeroAstro's NanoCore Electronics Bundle (NEB) is the heart of the SHERPA avionics, providing a very compact, highly integrated, reliable platform for planned servicing missions. In order to balance standardization with the flexibility needed to support different payloads, the NEB provides a consolidated bus architecture by integrating subsystem components common for missions of the proposed class, including:

- *Power Electronics*: The power controller card provides power regulation, conditioning, and distribution for up to 320 W.
- *Batteries:* The baseline design provides for either Li-Ion or Ni-Cad battery packs, with pack chargers and managers integrated into the associated safety housing.
- *Control & Telemetry:* The dedicated telemetry I/O card is capable of packaging and routing all commanding and data information between ground gateway(s). The NEB can accommodate multiple, additional I/O cards as necessary.
- *Communications:* AeroAstro's S-Band Receiver and Transmitter provide up to 1 Mbps downlink via an omni-directional antenna.
- *Processor:* PowerPC 750 based single card computer with 64 to 256 MB ECC memory.
- *Enclosure:* The modular VME card cage allows easy mounting of mission-specific components.
- *Software:* Includes foundation flight software.

Propulsion Module

SHERPA utilizes two different propulsion module options depending upon the requirements of the mission: a hybrid rocket system and an electric propulsion option that uses a Hall Effect Thruster (HET).

Hybrid Propulsion Module

The hybrid propulsion module (see Figure 3), being developed by SpaceDev, consists of a central hybrid fuel grain (Plexiglas) and nozzle, with four oxidizer tanks (nitrous oxide) surrounding it. The hybrid motor has an Isp of 260 sec and a maximum thrust of 222.4 Newtons.

A Propulsion Power Interface (PPI) board will monitor the health and quantity of propellant (polycarbonate) and oxidizer (NO2) components, regulate inhibits and plumbing, and enable/disable propulsive orbit-adjust maneuvers. In addition, the PPI will provide valve and switching logic necessary for the operation of each attitude control actuator, as well as applying the appropriate thruster Pulse Width Modulation (PWM) of requested commanding.

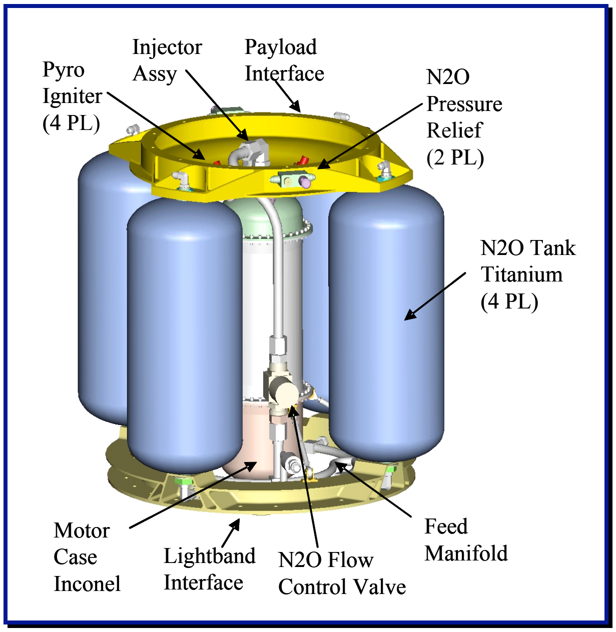

Figure 3. Hybrid Propulsion Module.
(Graphic courtesy of SpaceDev)

Electric Propulsion Module

The electric propulsion module (see Figure 4), being developed by Busek, consists of a Hall Effect Thruster (HET) and a small Xenon tank. The 200 - 250 W Hall thruster requires approximately 300 W from the bus. The HET is throttleable from 12 mN up to 16 mN, with an Isp ranging from 1000 - 1400 seconds, depending on the input power.

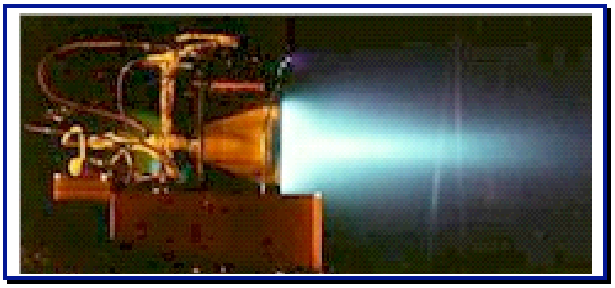

Figure 4. Electric Propulsion Module.
(Photo courtesy of Busek Co.)

A PPI board will monitor the health and quantity of propellant (xenon), verify the status of the annular cavity and anode/cathode, maintain required input power and current levels, regulate inhibits and plumbing, and enable/disable propulsive orbit-adjust maneuvers. In addition, the PPI will provide valve and switching logic necessary for the operation of each attitude control actuator, as well as applying the appropriate thruster Pulse Width Modulation (PWM) of requested commanding.

Attitude Determination and Control System (ADCS)

The ADCS module provides the control torques and command authority necessary to stabilize SHERPA, reject disturbances, and orient the spacecraft. In order to satisfy the vehicle and mission requirements for each configuration and sub-variants of the Mark II and Mark III SHERPA, several key ADCS trades were explored, including attitude control methods and their associated options, viable methods for determining spacecraft attitude and propagating state vectors, and available means for orbit and/or ephemeris determination. In keeping with the common-core system design strategy for SHERPA, preference was given to those options that represented viable solutions to all functional variants.

Vehicle Stabilization

Due to the nature of the mission operations, including the requirement for several orbit-raising maneuvers, passive stabilization is not a viable option for SHERPA. As the predominant source of disturbance torques arise from the propulsive maneuvers, careful attention is being given to the method of vehicle stabilization during these activities and the associated control versus propellant trade-space.

Currently under consideration is the provision for either a spin-stabilized or 3-axis controlled platform. While it is evident that spin-stabilization offers some benefit over a 3-axis stabilized system in the form of propellant savings, slosh management, and development risk, there is an inherent penalty suffered in operational flexibility to accommodate sensor and payload systems that may require low body rates for operation.

For the Mark II configuration, where it is desired that payload mass-faction be maximized, utilizing spin-stabilization during propulsive maneuvers for disturbance rejection and to mitigate torques associated with thrust misalignment, must be reconciled against the need for corrective maneuvers due to off-axis thrust inefficiency.

An analysis of the orbit adjust maneuvers was conducted in which the ΔV efficiency ($\eta_{\Delta V}$) was examined as a function of stack spin-rate.

$$\eta_{\Delta V} = \left(\frac{\left| \overrightarrow{\Delta V}_{DESIRED} \cdot \overrightarrow{\Delta V}_{ACTUAL} \right|}{\left| \overrightarrow{\Delta V}_{DESIRED} \right|} \right) \times 100\% \tag{1}$$

It was shown that for lower spin-rates, a higher amount of off-thrust-axis attitude error is realized. This activity, over the course of a fixed maneuver duration, results in the degraded in-track ΔV efficiency, necessitating a subsequent correction burn to be conducted (see Figure 5).

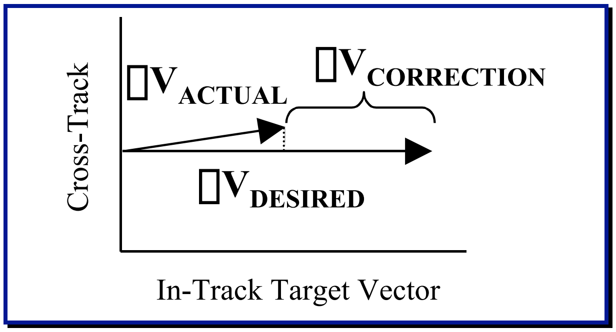

Figure 5. Delta-V Applied During Orbit Adjust.

The correction maneuver, applied with the benefit of an established value for the maneuver efficiency, is then able to complete the specified activity.

$$\Delta V_{CORRECTION} = \left(\frac{\left| \overrightarrow{\Delta V}_{DESIRED} - \overrightarrow{\Delta V}_{ACTUAL} \right|}{\eta_{\Delta V}} \right) \tag{2}$$

Under ideal conditions, with no thrust misalignment or other perturbative forces acting upon the SHERPA stack, an 80 second finite maneuver is sufficient to raise apogee to the target orbit of 704 km. As a consequence of the relative $\square_{\square V}$ associated with executing the maneuver with a small thrust misalignment, the performance sensitivity to spin-rate is evident. As shown in Figure 6, for a thrust misalignment angle of two degrees, the transfer orbit falls several kilometers short of the intended altitude for spin-rates less than 30 rpm.

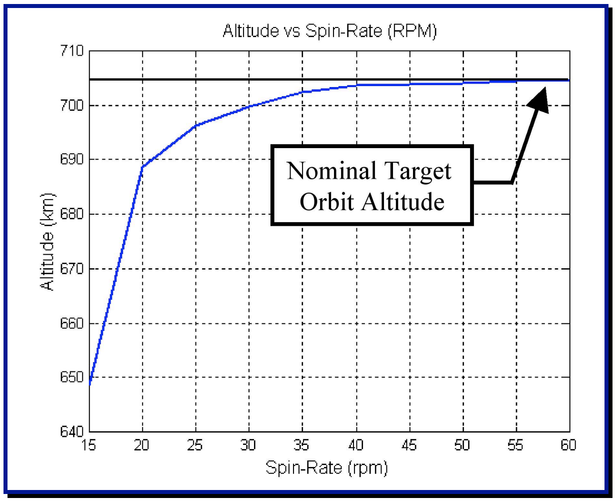

Figure 6. Transfer Orbit Altitude vs. Spin-Rate.

The sequence for the Hohmann transfer and associated correction maneuvers can be seen in Figure 7. In order to understand the sensitivity of maneuver performance to thrust misalignment angle and stack spin-rate, an end-to-end analysis was conducted to assess the total propellant required to perform the transfer and correction maneuvers.

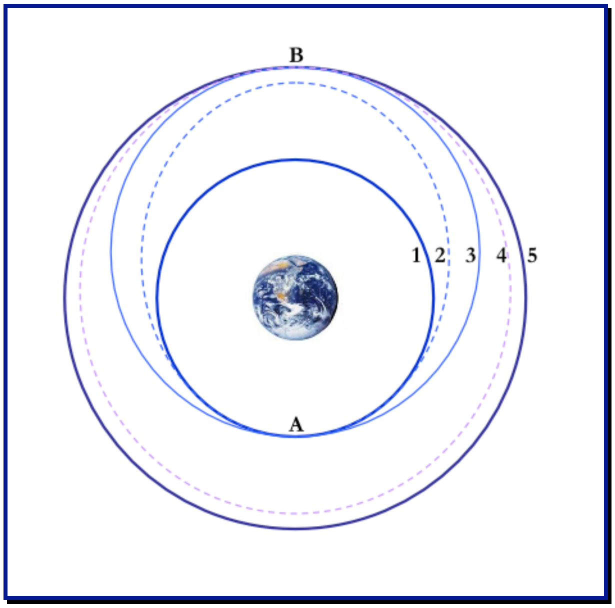

Figure 7. Hohmann Transfer Orbit Sequence with Correction Maneuvers:

1) **Circular parking orbit (350 km)**
2) **Initial Transfer orbit**
3) **Correction maneuver (transfer)**
4) **Circularize maneuver (704 km)**
5) **Correctionn maneuver (circularize)**

As seen in Figure 8, as spin-rate is increased, ΔV efficiency increases and performance quickly approaches that of the ideal case in which the only accumulated cost above that required for the maneuver itself is the propellant needed to spin the stack up and down before and after the orbit adjust, respectively.

A six-degree-of-freedom (6 DOF) simulation will determine the required attitude control propellant

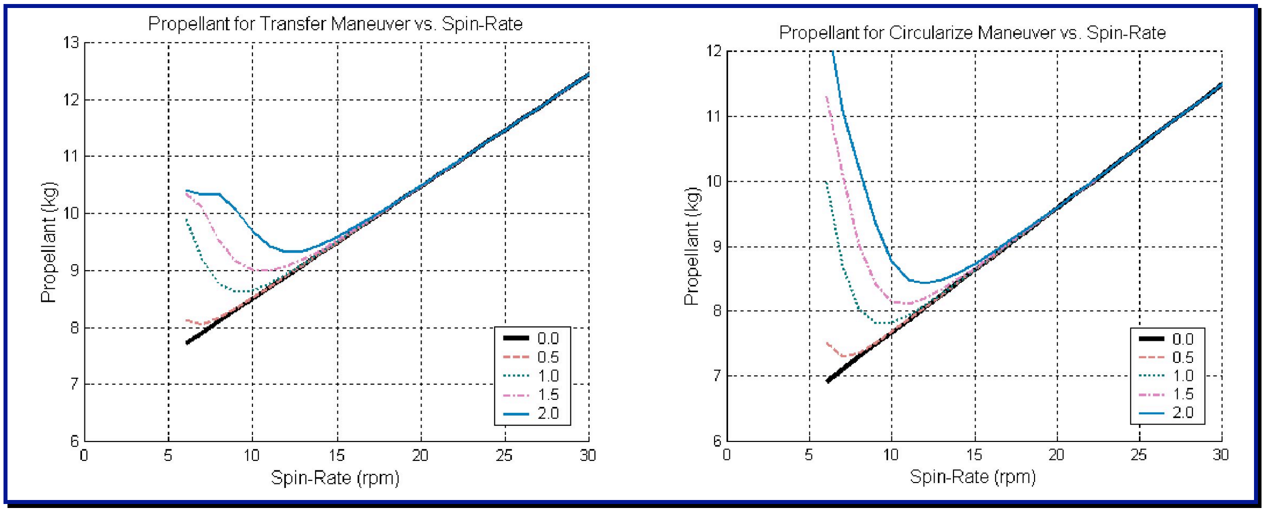

Figure 8. Required Propellant Sensitivity to Thrust Misalignment Angle (deg) as a Function of Stack Spin-Rate During Orbit Adjust Maneuver.

necessary to affect 3-axis control of the SHERPA stack during orbit adjust maneuvers. Based upon these results, a design decision for vehicle stabilization will be levied. Independent of choice of stabilization method, a small body rotation will be incited during periods of coast in order to provide a thermally benign and, if body-mounted solar panels are employed, a power-positive environment.

Attitude Control System (ACS)

Based upon the preferred stabilization methodology and mission requirements, several candidate ACS solutions were investigated. Reaction Wheel Assemblies (RWAs) were considered for their inherently greater pointing precision than even sufficiently small minimum-impulse-bit thrusters, but their use is predicated upon additional torque capability for periodic momentum unloading. Since fine pointing is not a strict requirement of the SHERPA ADCS, the added complexity and mass of RWAs were considered unnecessary for the baseline SHERPA – though they are regarded as a potential payload-dependent option for the SHERPA Mark III.

The program determined that a cold gas "bang-bang" control system that draws from the N2O reservoir of the hybrid propulsion module would best serve the baseline Mark II vehicle design. Disturbance torques are expected to be extremely small in the Mark II-E variant. Using appropriately sized actuators with a dedicated ACS plenum chamber will provide equivalent performance and control authority.

Attitude Determination System (ADS)

The SHERPA ADS must be accurate enough to sufficiently orient the SHERPA in inertial space and provide regular attitude updates such that all required orbit adjust maneuvers are conducted with acceptable precision and efficiency. This constraint is principally driven by the limited propellant capacity of the SHERPA available for the required plane change, orbit raising, CCAM, and de-orbit maneuvers (see mission timeline). In addition, during orbital maneuvers or periods of coasting in which sensor updates are not being taken or are otherwise unavailable, the ADCS must still be able to determine its state. To do so it must be capable of estimating its attitude by either propagating an analytic model of the vehicle or through Kalman filtering of measured inertial rates and accelerations.

Leveraging the capability of an integrated GPS receiver and Inertial Measurement Unit (IMU), the Avidyne Silicon Pilot (SP) will provide SHERPA with continuous update of position, velocity, and time data (PVT) from the GPS constellation, as well direct measurement of rates in six degrees. In addition to its integrated suite, the SP also features a PowerPC 550 processor on which the ADCS control logic and algorithms will reside.

The GPS nor the IMU alone can reliably determine the spacecraft attitude. While GPS is able to provide orbit-based reference information appropriate to the vehicle's center of mass (COM), it cannot determine the orientation of the space vehicle about it. An IMU, which is able to sense translation and rotation rates, its ability to resolve the attitude vector is dependent upon having accurate knowledge of initial conditions. Due to the uncertainty of deployment conditions, this system cannot reliably determine spacecraft attitude without use of an additional sensor solution.

A sun sensor and magnetometer combination is currently considered the baseline method for SHERPA Mark II attitude determination. For those applications requiring fine pointing and attitude knowledge under 3-axis control, a star tracker is the preferred measurement solution.

Orbit Determination

Orbit Determination (OD) computations will be conducted on the ground in conjunction with mission planning activities, with ephemeris information uploaded to the spacecraft. This approach is used to mitigate the on-board processing requirements for the SHERPA. Using various ranging technologies for OD, though traditional and proven, is unacceptable due to the requirements to coordinate ground station access with a variety of orbit and mission profiles, as well as the necessary capability of each facility for rapid acquisition and fast-tracking antennas in order to accommodate LEO operations.

By utilizing the GPS PVT solution provided by the Silicon Pilot, a high-fidelity orbit model may be established though normal telemetry downlink. In addition, because the GPS system is able to provide samples from its entire trajectory and not just a brief groundpass segment, the numerical basis for rectifying the orbital elements is greatly increased.

ADCS Architecture

A high-level block diagram of the proposed ADCS system is included in Figure 9 and identifies both required hardware components and software logic. As shown in the Signal Diagram (see Figure 11), in order to assure an integrated ADCS solution that is

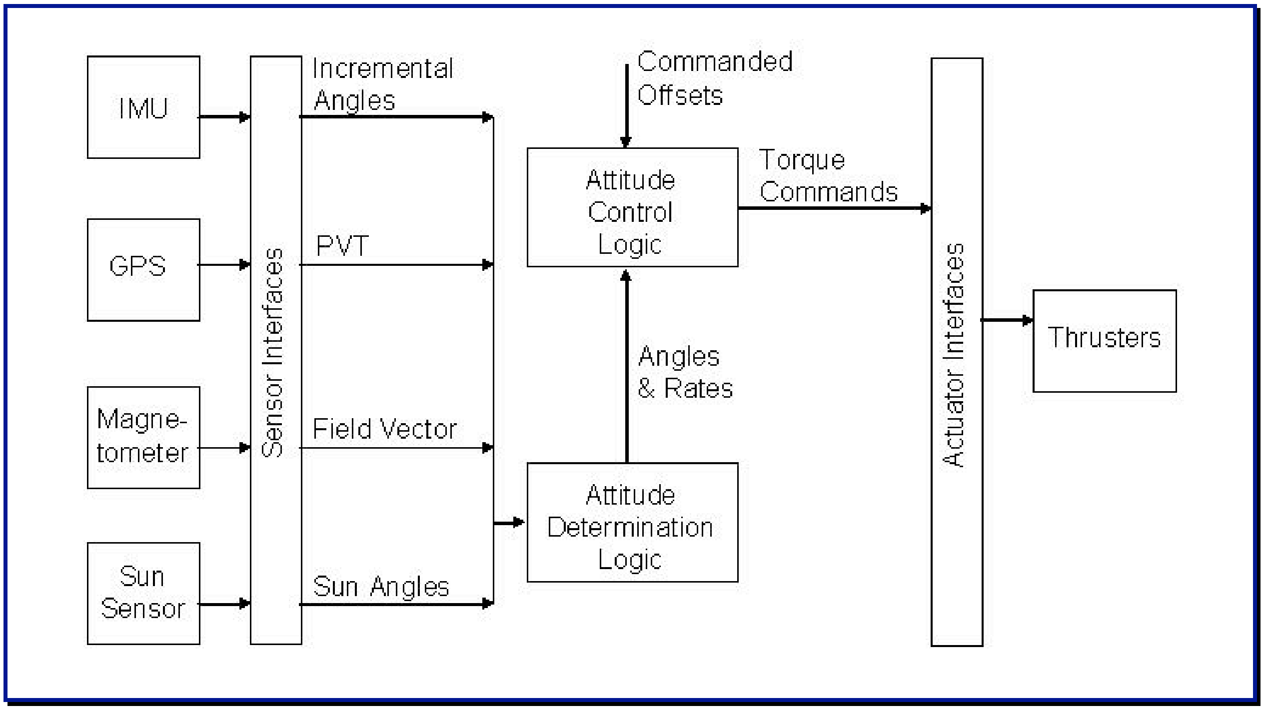

Figure 9. SHERPA ADCS Architecture with Potential Attitude Determination Sensor Options.

compatible with the SHERPA avionics core, information from attitude sensors will be routed through the Silicon Pilot, thereby leveraging the spare capability of its internal microprocessor for necessary computations.

Solar Array

A variety of solar array options are available for SHERPA, including body-mounted, simple deployable, and articulated or sun-tracking panels. Choice of substrate will be made as a function of power requirements and final panel sizing.

Mechanical and Thermal Systems

Although there are no mechanical devices identified for the baseline SHERPA Mark II design, Mark III configurations may require the use of deployable solar arrays, booms, or antennas associated with either payload or communication activities. In addition, these structures may be articulated and require flexible joint mechanisms, equipped with steerable or tracking capabilities, or be otherwise subject to packaging constraints necessitating complex deployment actuators.

Payload Separation System

The Planetary Systems Corporation (PSC) Lightband Separation System is a lightweight, low-shock, non-explosive solution for payload separation and staging for manifest on both the Space Shuttle and ESPA. Precision separation springs are sizable to impart a variable separation velocity with fully redundant switches and tensioners/de-tenionsers provided to assure system actuation. In addition, the bolt pattern and mechanical interface of the upper and lower rings to adjoining vehicles are completely customizable. The StarSys QwkSep Clamp Band Separation System is currently considered to be the reserve option.

SpaceFrame Structure

SHERPA uses the AeroAstro SpaceFrame structure technology for component mounting, shown in Figure 10. The modular architecture affords highly flexible and customizable spacecraft design and assembly.

For a fixed CAPE envelope, the Hybrid Propulsion Module configuration affords a payload height of 22.9 inches, while the Electric Propulsion Module configuration provides 31.5 inches at a slightly reduced cross-sectional allocation due to the requirement to accommodate a deployable solar array.

Thermal System

The thermal system consists of heaters and thermal blankets that will supply required operating conditions for sensitive avionics, while rejecting excessive heat loading as needed.

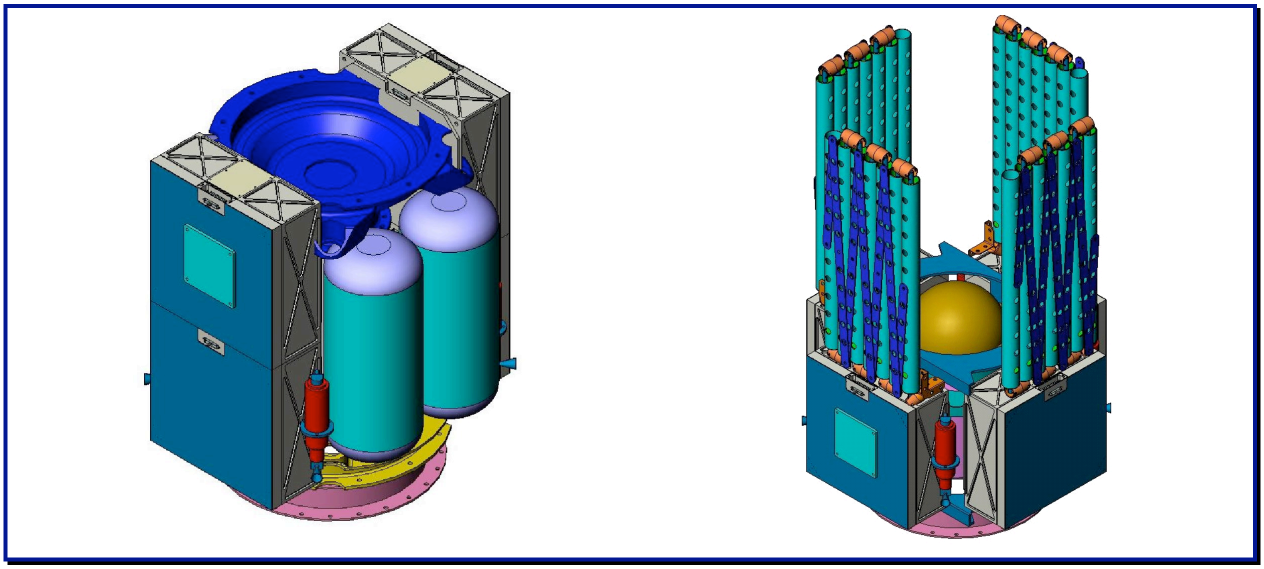

Figure 10. SHERPA Mark II Hybrid (left) and Electric (right) PM Variants, in Stowed Configuration.

System Block Diagrams

The block diagram of the SHERPA signal system is shown in Figure 11. The primary commands and data signals are routed through the VME Backplane, either directly or through the I/O boards.

As shown in this figure, the ADCS functionality is integrated around the Silicon Pilot. The attitude sensors, such as sun sensors, magnetometers, or a star tracker, interface directly to the Silicon Pilot, which directly controls them. In this configuration, the sensor data can only be accessed through the Silicon Pilot.

The PC&T provides the primary power conditioning and distribution. This distribution is accomplished either through direct connections between the PC&T and the component, or through the VME backplane. The PPI provides additional power processing to support the special needs (high voltage) of the specific Propulsion Module used. The PC&T controls the power flow to components.

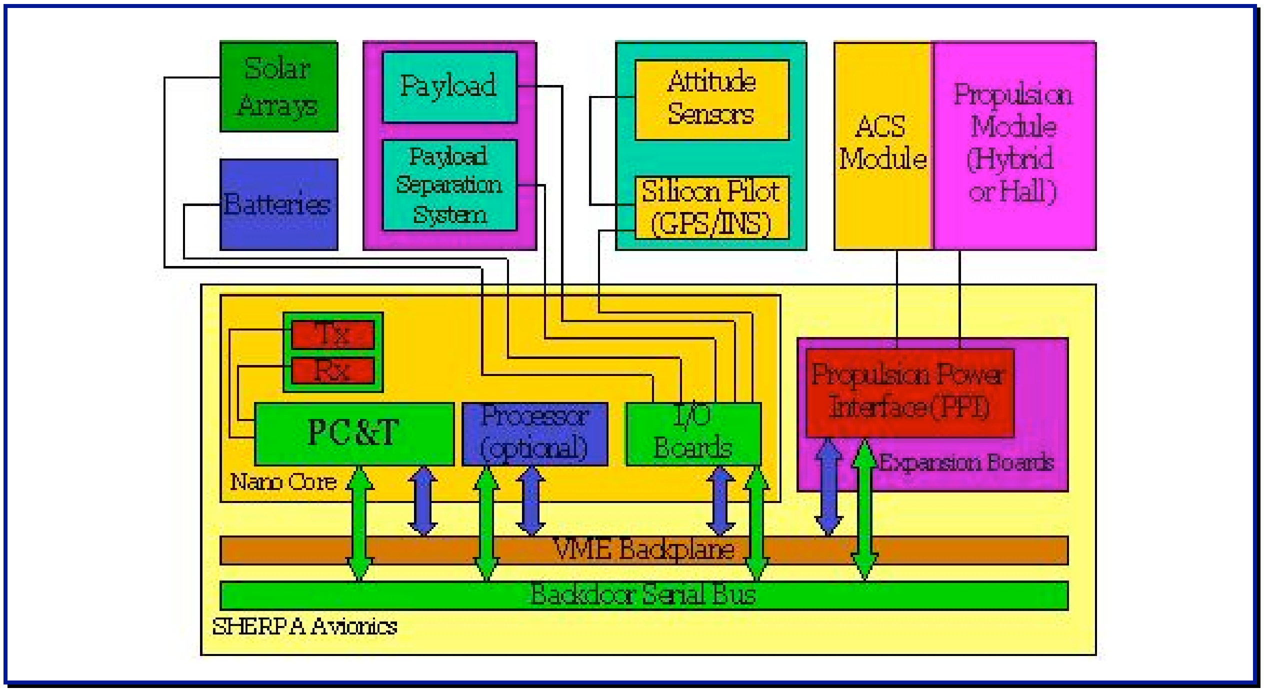

Figure 11. SHERPA Signal Block Diagram.

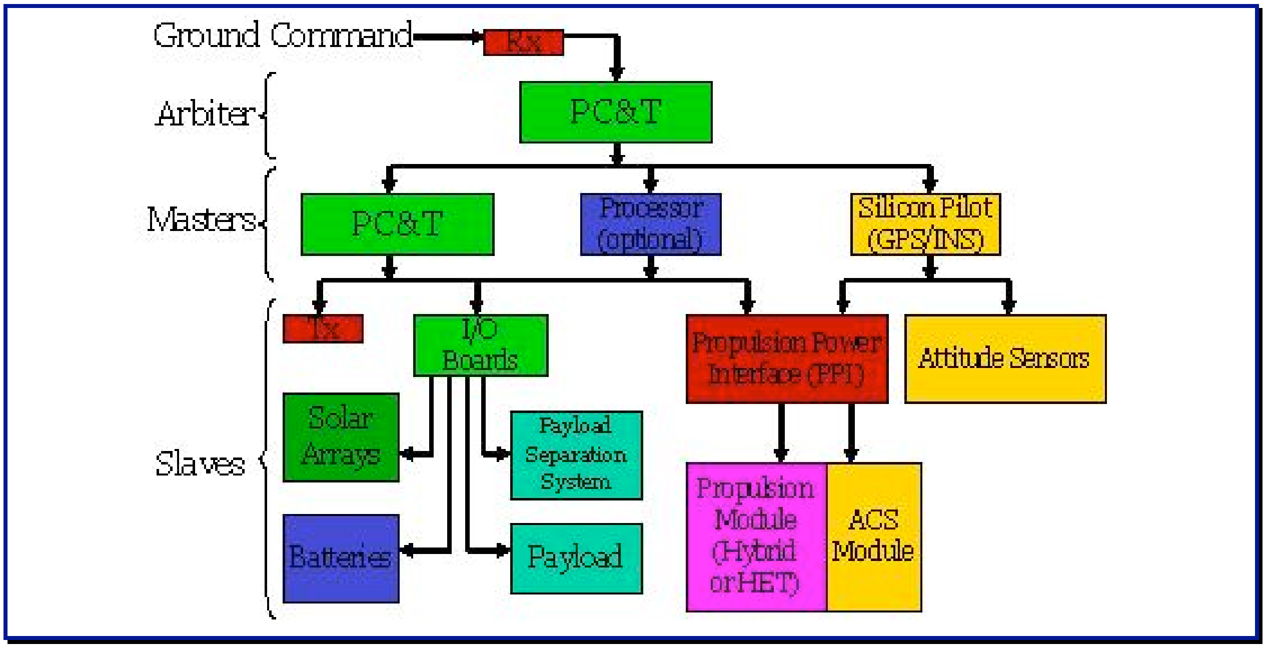

Figure 12. SHERPA Command and Control Hierarchy.

Within the command and control system, shown in Figure 12, the components are integrated as either Masters or Slaves. Slaves only respond to outside commands and provide data when requested, while Masters can issue commands and request data in addition to providing responses. Within the VME architecture, several Masters can share the Bus control, with the Arbiter determining which Master has control at a specific time.

Within the SHERPA avionics, the PC&T fulfills both Arbiter and Master roles. Other Masters include the optional processor and the Silicon Pilot. The remaining components are Slaves. Since the Silicon Pilot is not designed to interface directly to the VME Backplane, a special I/O Board is used to allow the Silicon Pilot to fulfill its Master role and control the Bus when needed.

While the PC&T controls the power to all components, the direct integration of the attitude sensors to the Silicon Pilot does not allow the PC&T (nor the optional processor) to directly access these units. Additionally, the Silicon Pilot is focused on ADCS tasks and only has control authority over the attitude sensors and the PPI, which controls the Propulsion Module and the ACS Module. The Silicon Pilot does not have control authority over PC&T, the transmitter, nor the I/O Boards.

SHERPA Applications

The SHERPA vehicle is currently being developed to support the needs of STP as a space-tug capable of delivering payloads from a low, STS-serviced altitude orbit, to a higher, long-life station. With this capability, however, myriad potential future applications exist, including:

1. Launch service from an Expendable LV (ELV) and EELV platforms as either a secondary or dedicated manifest. As a secondary payload, SHERPA would enable customers to deliver their spacecraft to any desired orbit regardless of the destination of the primary mission.
2. A SHERPA vehicle equipped with the AeroAstro Aerobrake technology would enable delivery of small payloads to LEO from a GTO injection.
3. Department of Defense missions such as space control could also utilize the SHERPA technology.

Conclusions and Recommendations

SHERPA addresses a critical need for improved access to space for small payloads. Successful development of SHERPA will also provide a host of technologies, components, and a system architecture suitable for a broad range of future missions

While additional work is needed, the conceptual design of SHERPA appears to meet the immediate requirements of the DoD. The flexible and modular architecture being used in SHERPA will produce a design that is capable of meeting the SHERPA mission requirements as well as several other national space mission goals.