SMEX•LITE - NASA's NEXT GENERATION SMALL EXPLORER

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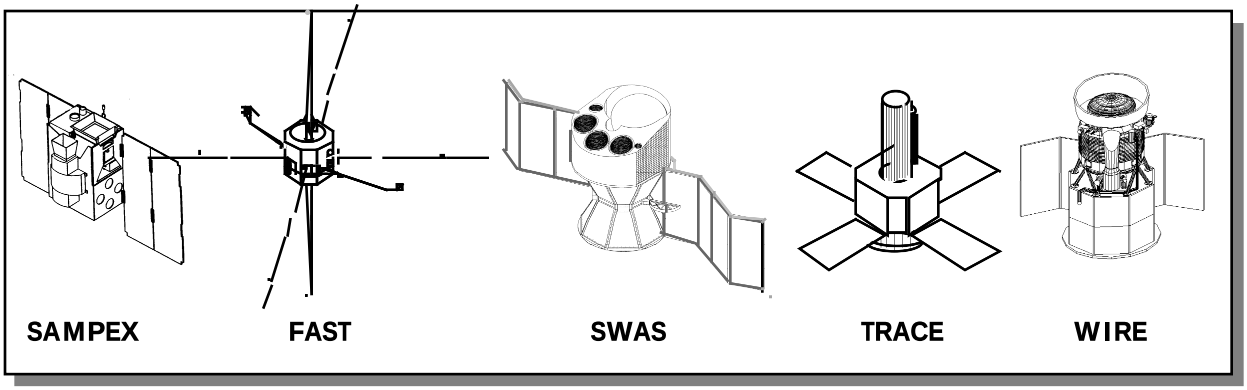
Abstract-- High space mission costs continue to be a major problem for the aerospace community. The National Aeronautics and Space Administration (NASA) Small Explorer (SMEX) Project has made great strides in reducing mission costs by implementing a building block architecture and streamlined mission operations. The project aims to substantially reduce both spacecraft and mission costs further through the introduction of advanced design tools and an advanced technology "function-sliced" architecture. Spacecraft autonomy will be extended such that classical mission operations will be eliminated altogether.

This paper will describe the fundamental elements of the planned cost reduction and the "function-sliced" architecture as well as cite those elements of the original SMEX design that have proven to be beneficial.

Introduction

The SMEX Program is one of NASA's unsung success stories. The program has produced spacecraft with extraordinary performance while fully embracing the essence of "smaller, faster, cheaper". Since its inception in 1988, the SMEX program has worked to provide frequent flight opportunities for highly focused and relatively inexpensive space science missions in the disciplines of astrophysics (radio, submillimeter, infrared, visible, ultraviolet, x-ray and gamma-ray astronomy, and relativity) and space physics (ionospheric, magnetospheric and heliospheric physics, solar physics, cosmic ray physics, and thermospheric and mesospheric physics) .

The first SMEX mission, the Solar Anomalous and Magnetospheric Explorer (SAMPEX), has accumulated over 4 years of successful on-orbit observations. The second and third missions, the Fast Auroral Snapshot (FAST) and the Submillimeter Wave Astronomy Satellite (SWAS)[1], are ready and awaiting launch on a Pegasus XL launcher. FAST and SWAS are planned to be launched in mid 1996 and early 1997. The fourth and fifth missions, the Transition Region and Coronal Explorer (TRACE) and the Wide-Field Infrared Explorer (WIRE), are in the detailed design phase preparing for launches in 1997 and 1998.



The program is unique in that it is multi-mission. A team has been formed and continues to work together across several mission boundaries. At least three mission developments are overlapped at any point in time and staggered such that the program is intended to launch a satellite every 1 to 1 1/2 years. The missions are to be developed for flight in approximately 3 1/2 years. The program is structured to accept increased risk to mission success in order to achieve reduced costs and a high flight rate.

Out of necessity, the program has developed and utilized a considerable amount of new technology hardware in order to meet the challenging power, weight, and volume limitations inherent in supporting complex experiments on a small satellite. Consequently, the SMEX Program is now seen as the ideal place to introduce new technology into spaceflight application.

The SMEX Program has already developed for flight the following items:

- Single board 80386/80387 microprocessor using surface mount and ASIC technologies
- Fiber optic spacecraft data bus
- Fully compliant CCSDS data system
- High density solid state recorders
- GaAs/GE solar arrays
- Super NiCad batteries
- Fully digital, 3-axis attitude control system
- Low power, high torque DC powered reaction wheels
- Autonomous, self-protecting spacecraft control techniques
- Portable ground stations

Additionally, the TRACE spacecraft will fly a multi-junction solar cell experiment. The WIRE spacecraft will use a composite structure to improve its weight performance.

The program's success has affected the manner in which NASA/Goddard Space Flight Center (GSFC) develops missions. The technical, management, and process techniques developed by the SMEX Project are being applied to the new MIDEX program. It has been the driving force for streamlining mission operations at GSFC.

However, as successful as SMEX has been, NASA budget reductions are forcing SMEX to evolve into a significantly less expensive program. SMEX, once the pathfinder, must establish even better means of conducting low cost missions. The program has set a goal of reducing the non-instrument costs by 50% while retaining the current level of performance. All SMEX•Lite missions (missions #6 and beyond) will be “designed to cost” with a fixed ceiling of $35M in ‘94 dollars. For a typical 3-axis pointer mission, the current SMEX designs incurs non-instrument costs of approximately $25M. This implies a major streamlining of an already rather lean program.

Restructuring of this magnitude requires fundamental changes in the way the project does business. The mission design, not just the spacecraft, must be optimized to reduce the workload and to shorten the development/integration/test activities. The SMEX•Lite architecture has been developed for this purpose.

The Original SMEX Design Approach

SMEX experience has shown that launch-vehicle constraints, fiscal constraints, and the wide variety of science objectives always require the development of mission unique capabilities. Structures and attitude control systems have been designed for the unique needs of each mission. The other major subsystem elements, however, have been taken from an inventory of spacecraft designs that were developed for the initial three SMEX missions. These items include the data handling system, power system, transponder, batteries, and standardized instrument and operational interfaces. This standardization was a practical consequence of the trade-off between optimum spacecraft design and the cost constraints and compressed schedules of the SMEX program. Reuse of common subsystem elements reduced technical risk, development time, and cost.

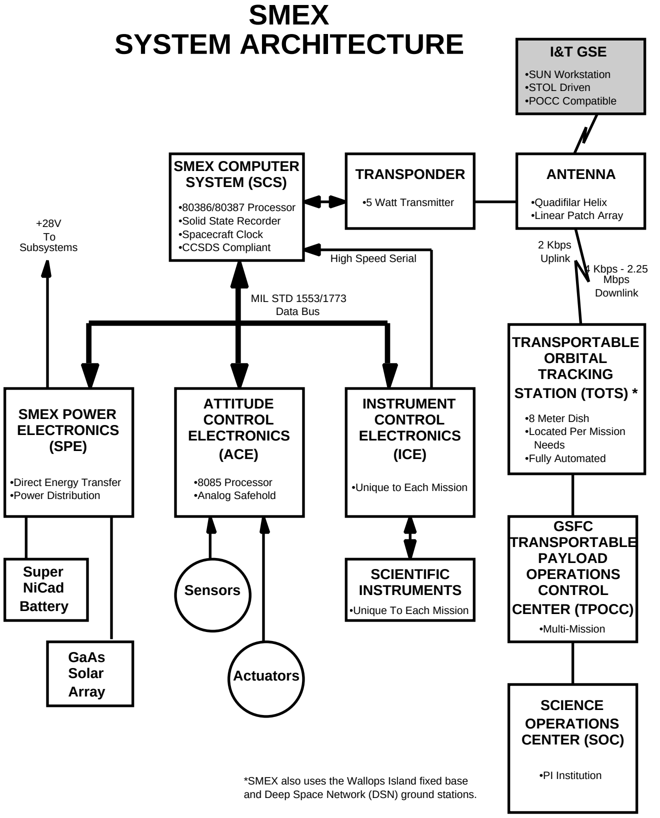
A large fraction of any spacecraft development cycle involves the definition and verification of interfaces. Consequently, SMEX utilized a distributed system architecture which decouples the spacecraft functional elements at the subsystem level with standard hardware and software interfaces. This has allowed for efficient parallel development and testing.

The use of standard interfaces has simplified spacecraft integration. A standardized ground operations interface (specifically the Consultative Committee for Space Data Systems (CCSDS) standard) allows for multi-mission utilization of both Ground Support Equipment (GSE) and operations resources.

The Current SMEX Spacecraft Architecture

The current SMEX spacecraft system architecture (Figure 1) is versatile and high-performing. This basic architecture was used for the SAMPEX and the SWAS missions. It is being reused extensively on the TRACE and WIRE missions. All SMEX spacecraft are single-string.

Considered to be radiation tolerant, this spacecraft design can be flown in all low Earth orbit environments. All subsystems communicate through a MIL-STD-1553/1773 data bus.



*SMEX also uses the Wallops Island fixed base and Deep Space Network (DSN) ground stations.

Figure 1. Current Baseline SMEX Spacecraft Architecture

The Spacecraft Computer System (SCS) is the core of the data system. It controls all spacecraft operations, supports attitude control system computations, collects and stores telemetry, maintains time, and interfaces to the instrument. The SCS can provide instrument support such as command and control, data manipulation, and data compression. The SCS also controls the firing of the spacecraft pyrotechnic devices.

The SCS is based on a 32-bit, 386 computer with a math coprocessor capable of floating point operations. The SCS ingests ground commands and downlinks both real-time and stored telemetry. All telemetry is encoded to reduce errors.

Bulk data storage is accomplished using volatile, static-random-access-memory devices with error detection and correction. The bulk memory is uniquely sized for each mission in order to minimize physical size, mass, and cost. Bulk memory is limited to approximately 1 gigabit due to downlink capabilities during a ground station pass. Typically only 60% of the pass duration can be allocated for telemetry downlink. The remainder of the pass is used for commanding and tracking operations.

The SMEX spacecraft uses an S-band transponder with 5 watts of RF power. It can support data rates up to 4.5 Mbits/second. For orbit determination, the transponder also performs coherent Doppler reflection and range-tone re-broadcast. The ground processes this data to update the orbit ephemeris. The SMEX spacecraft rely primarily on Wallops Flight Facility and the Deep Space Network for ground station coverage.

The spacecraft is powered by a direct energy system. Unregulated +28 volts power is taken directly from the solar arrays and distributed to the subsystems. All five SMEX missions use gallium-arsenide solar cells because of their higher power densities. A nickel cadmium-type battery is used to power the spacecraft during the eclipse periods of the orbit. Excess power is dissipated in shunts mounted on the backside of the solar arrays. TRACE and WIRE are working towards the total elimination of the shunts. The SPE controls battery charging, distributes and monitors the +28V power, and provides fusing as required.

The Attitude Control System (ACS) is a mission unique system. The SCS processor supports a digital attitude controller, which typically is incorporated for science pointing mode operations. This controller collects sensor data and issues actuator commands through the Attitude Control Electronics (ACE) box. It also provides onboard attitude determination and orbit propagation. The ACE serves as the hardware interface for the ACS, and is also used to provide a software-independent safehold controller. The safehold controller is used for initial attitude acquisition and on-orbit emergencies. ACS performance depends entirely on the hardware devices that are flown and the specific spacecraft and instrument characteristics. ACS sensors and actuators are chosen to support the specific requirements of each mission.

Thermal designs are also unique to each mission. Power limitations on the SMEX missions required primarily passive designs that rely on fixed radiators, blankets, and selective coatings. The spacecraft controls both the survival and operational heater busses. Strategically placed thermostats cycle power to the heaters as required.

SMEX instruments have contained their own controller to allow a clean interface with the spacecraft and to facilitate testing and integration. The instrument/spacecraft data-system interface have generally been via the MIL-STD-1553 bus for commands and low rate telemetry and via the RS-422 serial port for high rate telemetry.

This architecture has accommodated a wide variety of mission requirements. The capabilities are summarized in Table 1.

Table 1. SMEX Capabilities & Design Features

SMEX CAPABILITIES

Instrument Weights	45.4 - 91 Kg
Instrument Power	40 - 150 Watts
Science Data Capacity	0 - 130 Mbytes Per Day
Instrument Data Rates	0 - 100 Kbps
Real-Time Telemetry Rates	4 Kbps - 2.25 Mbps
Uplink Command Rates	2 Kbps
Number Of Downlinks Supported	Twice Per Day To Once Per Orbit
Attitude Determination	±2 Deg To ±38 Arc-Secs
Orbit Determination	7 - 30 Km
Radiation Environments	3 - 30 Krad
Mission Lifetime	1 - 3 Years

SMEX DESIGN FEATURES

- 24 Hour Autonomous Operation
- Independent Safehold
- Onboard Attitude Determination
- Onboard Orbit Propagation
- Onbaord Maneuver Calculation
- Onboard Data Compression
- Bulk Data EDAC
- Pyro Firing Circuitry
- Standard Data Bus
- High Speed Serial Data Ingest Port
- Power Distribution
- Instrument Overcurrent Protection
- Transportable Ground Stations

SMEX•Lite Cost Reduction Strategy

Further cost reduction within SMEX required that the whole team had a thorough understanding of where the program had previously spent its funds. An analysis of prior mission costs helped to focus the SMEX•Lite restructuring on the real cost drivers (Figure 2). Approximately 1/5 of the non-science cost went into Mission Integration expenditures. These included project support capabilities (administrative, configuration management, scheduling, transportation, launch site field operations, etc.), integration and test (I&T) support, environmental test, preparation for flight operations, and flight assurance activities. The dominant Mission Integration cost was the ***preparation for flight operations***.

The remaining 4/5 of the non-science cost went into the design, development, assembly, and functional testing of the spacecraft. Most of these expenditures were for ***design and test engineering*** activities. Except for the battery and solar array, very little money was directly spent on hardware purchase or manufacturing.

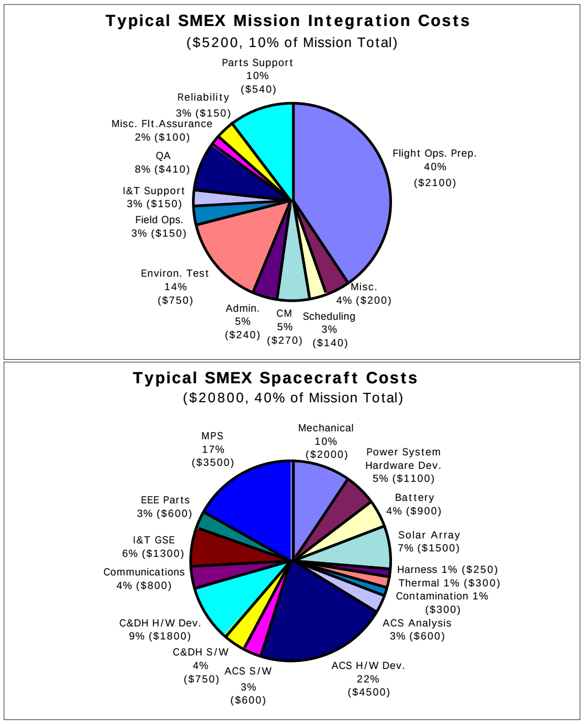


Figure 2. Current SMEX Cost Distribution

The cost analysis also revealed the strong points of the current SMEX approach. It was quite interesting to note that flight software accounted for only 7% of the spacecraft cost. Consequently, SMEX•Lite will migrate more functions from hardware to software.

It quickly became obvious that from a management perspective the new approach must achieve major reductions in:

- design and test engineering,
- battery and solar array hardware costs, and
- flight operations preparation.

From the engineering perspective the new approach had to:

- have less to design,
- be both easier and quicker to design,
- be easier to modify for mission uniques,
- eliminate duplication of similar generic technical activities between subsystems,
- be simpler to test,
- require much less unique GSE, and
- be easier to operate.

Whatever SMEX•Lite evolved into, it must require much less engineering effort to develop and to fly.

SMEX•Lite Architecture

It was clear that the current SMEX architecture was distributed at too high of a level to meet the SMEX•Lite needs. The original design optimizations were made at the subsystem level, often crossing both physical and functional boundaries within the system. Consequently, design modification, even for minor changes, tended to always have significant ripple effects within the entire subsystem box. This consumed a lot of engineering resources. The new approach must break apart the subsystem boxes into smaller, more distributed elements that encompass only one basic function each. These “functional slices” must be easy to interface, essentially transparent to each other, much like the “plug and play” equipment found within the commercial computer industry. This would facilitate quicker development by allowing more parallel efforts. This concept resulted in the definition of a truly open architecture for space mission design.

The open architecture (Figure 3) concept includes not only the electronics, sensors, and actuators but also the software, solar array, the mechanical system, and the ground operations system. It is easily configurable for any SMEX mission, can be quickly integrated, is open to technology upgrades for all functions, and exceeds the current level of SMEX performance.

The SMEX•Lite architecture relies heavily on industry standards to couple (or rather, decouple) the functional slices. The entire spacecraft is controlled by one 32 bit microprocessor. Functions which require high speed access to the processor such as telemetry data storage (and manipulation) and downlink are connected via a standard PCI bus. Functions which require only routine support from the processor (including the instrument) are linked on the standard 1553 data bus. High speed/high volume data transfers are conducted over a dedicated medium. Analog connections are limited simply to distribution of unregulated 28 volt power. Except for the reliance on the flight processor, each functional slice is independent of the others. Each functional slice is packaged on an industry standard military SEM-E stretch circuit board. The total amount of spacecraft electronics has been reduced by a factor of 4, from 1450 sq. in. to only 350 sq. in. of circuit board. This was made possible only through the extensive use of surface mount, LCC packaging and programmable logic device (FPGA, PALS, etc.) technology.

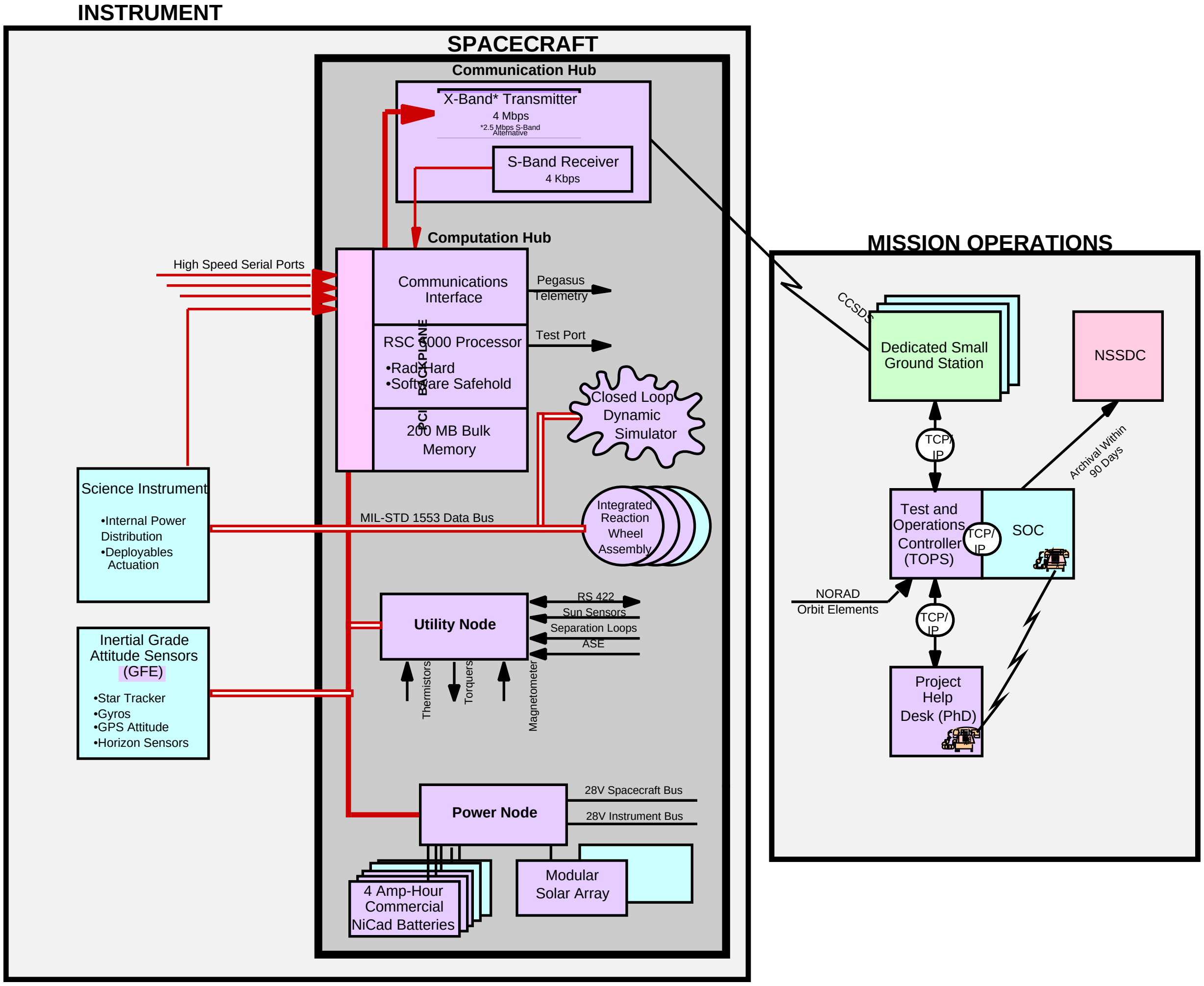


Figure 3. SMEX•Lite Architecture

This heavy reliance on programmable devices allows for rapid and thorough prototyping via convenient workstation based simulation design tools. Part programmability provides the flexibility to make changes to flight circuitry by simply replacing a part with a reprogrammed version. This greatly shortens the debug cycle and even allows for relatively easy modification of flight hardware late in the development cycle. Gone are the days of iterative breadboard fabrication and testing. In many cases there is now no need for the development of Engineering Test Unit (ETU) hardware.

SMEX•Lite will utilize a very small "core team" of designers staffed from the different subsystems specialties for its design and test activities. This team, led by a systems engineer, will participate in the design of all of the functional slices. The purpose of this team is to ensure that the design of similar functions (A/D, MUX, amplifier, interface support, etc.) which are needed within the different functional slices are approached from a common basis in order to minimize duplication of effort. This should also result in better implementations due to the merging of experiences from a broad spectrum of applications. Standard interfaces also mean that the software can be more structured. This team will be co-located, with a common design lab equipped with the appropriate design tools. A similar approach will be used to optimize the performance of the three (Command and Data Handling (C&DH), ACS, I&T GSE) major SMEX software groups.

The use of a standard card size allows for one mechanical/thermal box design. The use of standard card interfaces have a ripple effect on the GSE as well. Most functional slices can be tested using very similar GSE, usually simple, inexpensive PC's.

The SMEX•Lite architecture requires considerably less design work. The decoupling effect of the functional slices eliminates a large amount of electrical engineering activity. Unlike the original SMEX architecture where the internal box contents of each subsystem were tightly coupled in order to conserve power, weight, and volume, the decoupled functional slices of the SMEX•Lite architecture allow the mission designer to easily alter the content of the spacecraft systems. The use of standard interfaces allows for quick integration of a new function. Functions which are not needed can be simply removed without any deleterious affect on the other elements of the mission. In short, **the SMEX•Lite design is optimized for change**.

Within SMEX•Lite, the Principal Investigator (PI) must weigh the importance of precision attitude control to the conduct of the scientific investigation. The increased cost of inertial grade sensors must be traded against the resulting decrease in available funding for the instrument. Each mission configuration must be optimized to meet the stringent cost constraints. ACS sensors and actuators are interfaced on the data bus in order to make this technically easy to accomplish.

Solar arrays tend to fall victim to the mechanical packaging trade-offs conducted during the spacecraft design process. As a result, the arrays are never quite the proper dimensions to allow the use of previously qualified cell configurations. New string layouts and manufacturing tooling must be developed. Consequently, solar arrays are very expensive. This is strictly due to the custom nature of their designs and the perceived need to qualify each specific process associated with the build of every array. The basic material costs are not that expensive.

SMEX•Lite will extend the plug and play approach of its electronics to achieve cost savings on both the solar array and battery. Standard solar array "platelets" will be developed. These platelets consist of small full string cell configurations assembled on a standard composite mini-panel (Figure 4). These platelets are then assembled by the end user into a larger framework, forming the completed solar array. The platelets can be ordered in lots, qualified and stored much as electronic parts, later being stuffed into each mission unique solar array geometry.

This allows for easy technology upgrades and mixing of cell types within a single solar array. There may be, however, a small penalty in solar array packing efficiency for some missions.

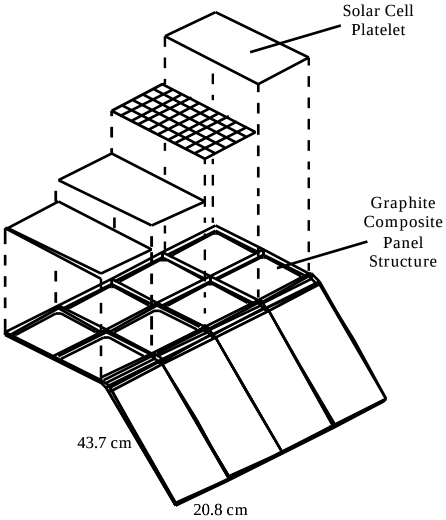


Figure 4. Solar Array

The SMEX•Lite power system is configured to utilize multiple 4 amp-hour NiCad batteries with independent V/T and amp/hour integration controllers. Mission requirements will define how many units, up to five, that will be used. Each battery is comprised of 22 industrial grade D cell batteries assembled into a single package. Output of the batteries are tied together with the solar array and regulated with a pseudo peak power tracking controller implemented digitally using a buck regulator topology.

The dramatic reduction in the size of the SMEX•Lite spacecraft electronics has now made it practical to consider a standard mechanical bus configuration. If the “spacecraft” is small enough it can be considered as a simple clip-on resource for the instrument. The SMEX•Lite spacecraft can be packaged in a structure that is only 12 inches tall (Figure 5). This small size has allowed us to go to a one-piece aluminum casting for the primary structure, eliminating costly piecepart design, fabrication, and assembly. Electronic boxes are incorporated directly into the structure. Many different instrument configurations can be accommodated. This leaves the majority of the launch vehicle volume available for instrument use. The modular solar array can be configured and attached in a variety of ways. Again, the SMEX•Lite design is optimized for flexibility and change with very little, if any, penalty to the user. Besides being inexpensive and multi-mission, this design allows for easy tabletop integration of the spacecraft elements prior to instrument arrival.

SAFEHOLD

The original SMEX system relied on an independent analog safehold controller to serve as the ultimate safety net for spacecraft protection against a variety of hardware, computer, and/or software problems. This approach required a significant amount of analog circuitry and interconnects in order to couple all of the necessary functional elements.

SMEX•Lite has eliminated this controller to further streamline the spacecraft system. The function of safehold, however, is retained in the form of an extremely simplified software control algorithm within the spacecraft processor. It executes in boot mode, directly out of PROM and is structured to be self resetting and SEU tolerant. This approach requires considerably less hardware than before, which should improve reliability.

This approach towards safehold is consistent with the single string configuration of the SMEX spacecraft. The SMEX•Lite safehold mode relies only on a small subset of the “mission critical” spacecraft hardware. The failure of any one of these key elements (i.e., processor, data bus, critical sensor or actuator, etc.) that cannot be cleared by a system reset or power strobe will result in the termination of the nominal science mission. The acceptance of this obvious dependency greatly simplifies the scope of the safehold controller. In a cost driven environment it makes little sense to fly additional hardware to preserve a spacecraft that can no longer conduct its primary mission.

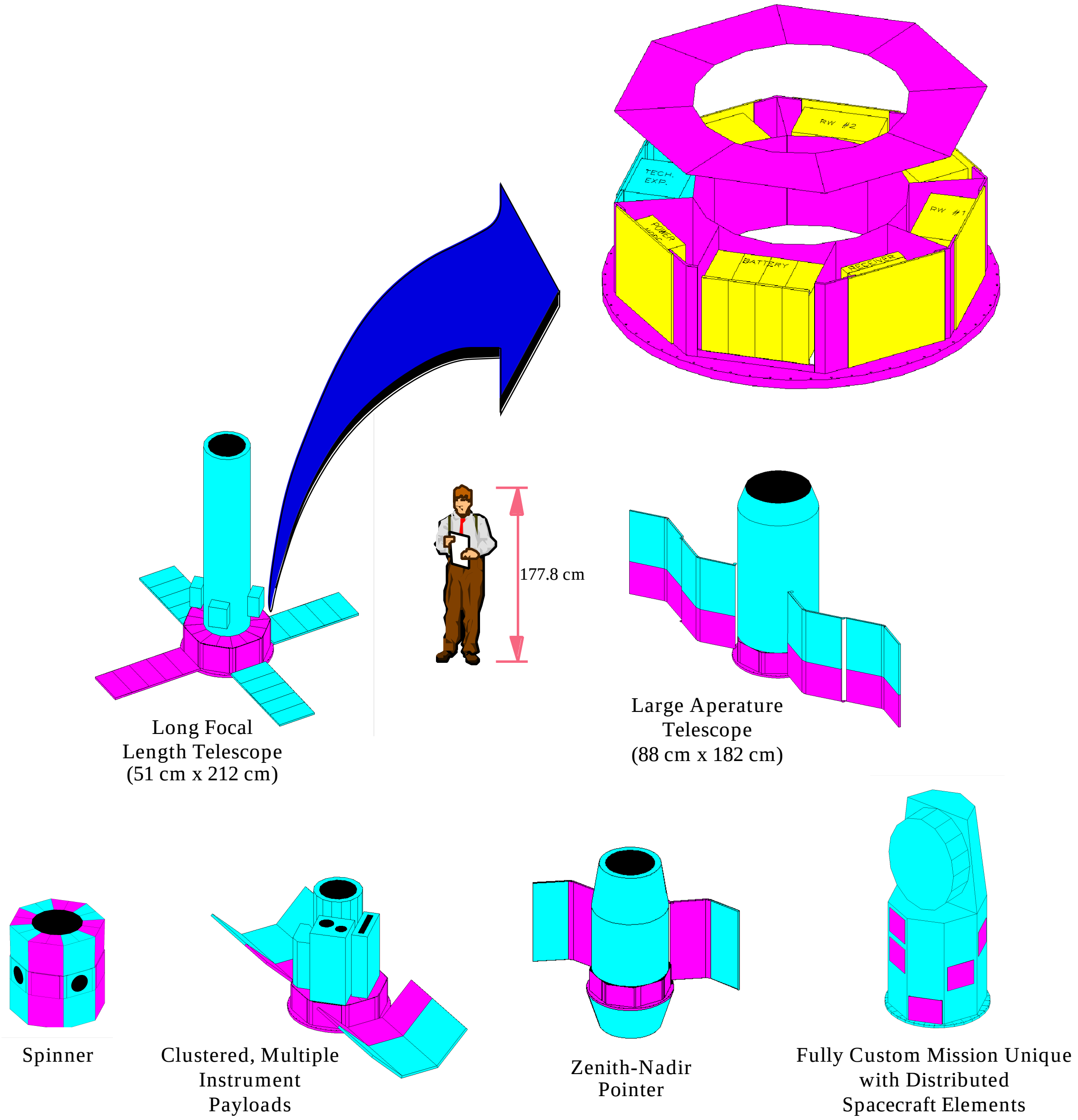


Figure 5. SMEX•Lite Mechanical Architecture

Spacecraft Test & Flight Operations

The decoupled functional slices allow for much testing to be conducted in parallel, independent of each other. In fact, it is now quite practical to literally integrate all of the spacecraft electronics on a table top and conduct a large percentage of the traditional “system” tests prior to observatory integration. SMEX•Lite plans to conduct most of its software development activities using simply a PC representation of each of the functional slices. This flexibility in testing should provide for a much more efficient and rapid system I&T.

Spacecraft dynamic testing usually involves separating hardware interfaces and injecting simulated data into the system. This coupling of the testing to the hardware configuration consumes a lot of time. Since the spacecraft processor has excess capability, the SMEX•Lite flight software will access this simulation GSE (i.e., the closed loop dynamic simulator) over the spacecraft data bus, thus simplifying the integration and test process and minimizing the amount of spacecraft configuration changes.

The Test and Operations Controller (TOPS) system is used to both test the spacecraft and conduct mission operations. Data is transferred through the ground system using standard TCP/IP protocols instead of via custom NASA protocols. A small, portable ground station will be used to provide communication to and from the spacecraft. These ground stations will be geographically sited wherever necessary to support the mission.

The key to flying lower cost space science missions is to minimize the burden on flight operations, both the personnel and the equipment. SMEX has accomplished this by building smart spacecraft that are insensitive to operational error and capable of operating for extended (12-24 hours) periods of time without ground intervention. These capabilities will be continued with the SMEX•Lite approach. The PI is given the full responsibility and freedom to develop the observing timeline at the Science Operations Center (SOC). The completed timeline is simply passed on for command construction and uplink to the spacecraft. Onboard spacecraft error checking and ACS and power system performance monitors will reject any science observations that threaten spacecraft health or safety, as well as watch for anomalous conditions that may threaten the mission. Autonomous safing actions are initiated by the spacecraft to protect itself [2]. Orbit ephemeris updating and clock maintenance will be performed autonomously onboard the spacecraft.

The spacecraft is also used to perform typical functions that are commonly done on the ground after receiving stored telemetry. For example, the ACS performs the definitive attitude and orbit determination onboard and places the solutions directly into the science data stream for delivery to the PI. The spacecraft data system separates science and engineering telemetry for easy review on the ground. All of these features make the spacecraft easier and more efficient to operate.

Within the SMEX•Lite architecture the PI is responsible for deciding the importance of capturing the science data. Unlike current ground systems which are optimized to maximize the probability of capturing every bit of data, this ground system is configured to capture most, but probably not all, of the data. If higher reliability is required then the PI must trade off the increased ground costs against reduced instrument funding. The PI will be entirely responsible for all data processing, from level 0 through final archival within the National Space Science Data Center (NSSDC). The SOC will become the mission operations center and is run by the Principal Investigator (PI). Since SMEX is a continuing, multi-mission project it will retain the capability, through the Project Help Desk (PHD), to review engineering telemetry and provide troubleshooting support when required. If the SOC has difficulty with the operation of the spacecraft, the PI would simply call the SMEX project to request assistance. Engineering data would then be passed via commercial data lines to the PHD at GSFC for review by SMEX engineers. Response time could be as much as several days, but this approach greatly streamlines ground operations compared to current standards. It is made practical by the acceptance of modest risk of occasional loss of data coupled with the high degree of autonomy imbedded within the SMEX spacecraft.

SMEX•LITE COST REDUCTION RESULTS

The SMEX•Lite architecture shows great promise for meeting the original goals of the program rescope. A grassroots cost estimate of a typical 3-axis pointer mission projects the non-instrument costs to be approximately $13M, with a distribution as shown in Figure 6.

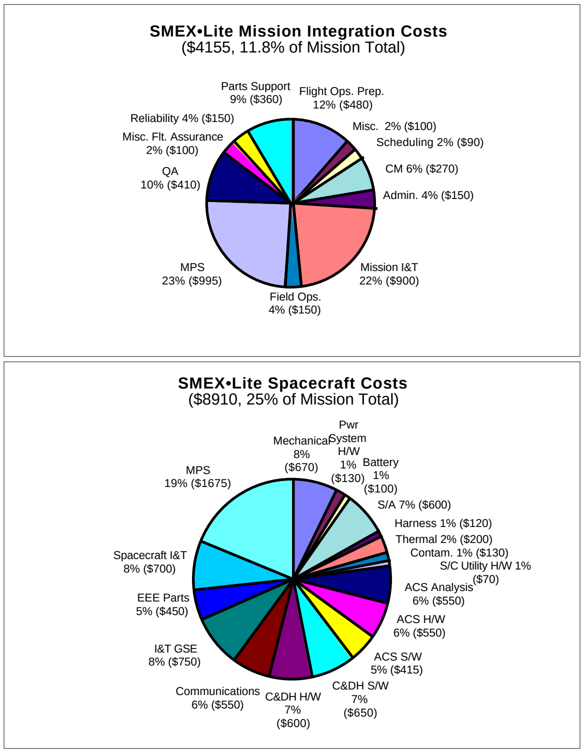


Figure 6. SMEX•Lite Cost Distribution

It is interesting to note that the total electronics costs from all subsystems have dropped by the ratio of reduction in circuit board area. Flight software costs have been reduced by 30%, primarily due to our high degree of reuse, but now represent a greater fraction of the total spacecraft costs. Flight operations are dramatically improved.

CONCLUSION

The SMEX•Lite system design provides an open system architecture suitable for use on small spacecraft. Its function-sliced configuration allows for easy expansion or contraction of capabilities such that both low and high performance missions can be efficiently supported. This plug and play approach is optimized for reduced development time, simplified integration and test, and adaptability to change. It relies heavily on standard interfaces to achieve its flexibility and on software to achieve its performance.

The SMEX•Lite provides more than twice the basic physical resources (power, weight, and volume) to the instrument than its most challenging missions in the past (Figure 7). This will enable bolder and more extensive scientific investigations to be conducted.

The SMEX•Lite approach has been facilitated by the recent maturation of spaceflight worthy programmable logic devices (PLD's). The modern, computer aided design tools that support the PLD's will greatly streamline the design process, allowing rapid prototyping and detailed analytical simulations. Personal computer based GSE will make testing more economical.

Classical mission operations have all but disappeared with the SMEX•Lite architecture. The simplified operations infrastructure will dramatically lower mission operations costs. Spacecraft autonomy will allow for a much more relaxed operations environment, promoting even greater flexibility and innovation in the future.

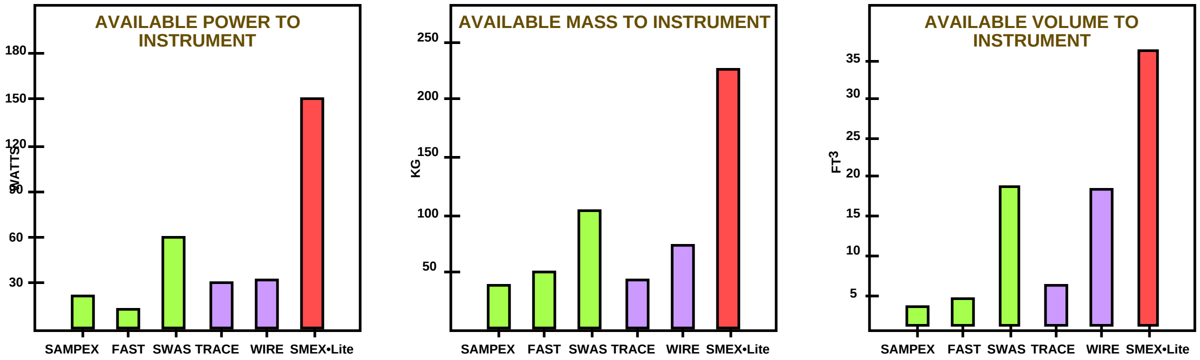


Figure 7. SMEX•Lite Physical Resources

BIOGRAPHY

The author is currently the project manager for SMEX. He has been with the project since its start where he previously served as the Chief Systems Engineer. Mr. Watzin has been employed by NASA since 1980 and has a background in Attitude Control and Systems Engineering. He earned a B.S. in Mechanical Engineering from the University of South Carolina and a M.S. in Dynamics and Control from the School of Aeronautics and Astronautics at Purdue University prior to working for NASA.

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