Systems Engineering and Integration of Advanced Technologies for Small Satellites at Phillips Laboratory Directorate of Space and Missiles Technology

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Summary
This paper will review some of the satellite technology developments and the system engineering approaches in use at the Phillips Laboratory Directorate of Space and Missiles Technology (PL/VT), which are relevant to increasing the capability of small satellites.

The paper will cover structures, materials and controls, space power technology, thermal management, and electronics developments that enable high performance small satellites. In the last section of the paper we will cover some mass and performance advantages that can be obtained by integrating technologies at the system level and developing new concepts that cross the bounds of traditional spacecraft subsystems.

Structures, Materials and Controls:

Structures, Materials and Controls technology is rapidly increasing the capability of small satellites while greatly reducing their weight. Present day emphases in this area are on composites, smart structures, and adaptive control.

<u>Payload Isolation System</u>. Phillips Laboratory Structures and Controls Division (PL/VTS) is developing a Payload Isolation System which will reduce launch vehicle loads and the launch vibration environment which spacecraft experience. This will reduce spacecraft failures during the launch phase, relax loading design requirements for the spacecraft structure and reduce the cost, size, and weight of some spacecraft components.

<u>Shape Memory Actuated Release Devices (SMARD)</u>. The objective of this program is to use shape memory materials in a release device to take the place of pyrotechnic devices for separating satellites and deploying solar arrays and other structures. These new devices will eliminate pyroshock and contamination. As a result of the reduced shock loading, the weight of satellite structures can be reduced by reducing structural design requirements. As an added benefit, the flight hardware can be tested on the ground and reset for launch, while maintaining the same quick release capability. Also, eliminating pyrotechnic devices reduces safety hazards at the launch site.

<u>Smart Structures</u>. VTS's work with smart structures will increase the damping characteristics of a spacecraft structure and allow for a net decrease in weight. In the past, spacecraft structural members were made thicker and heavier to increase spacecraft structural stiffness primarily to meet payload jitter requirements. However, with smart structures it is possible to reduce the weight of the members and the amount of vibration seen by the payload by implementing active control.

This program has several projects underway in the area of smart structures. One is the Advanced Control Technology Experiment (ACTEX) which is geared towards laser communications. The goals of ACTEX are to verify active vibration suppression technology used on actual space hardware and to develop an active controls experiment that simulates the flight environment.

Another program is the Modular Control Patch. This program will develop a control system which contains sensors, control electronics, and actuators in a thin composite patch that provides damping capability to space structures.

A third is the Ultra Quiet Platform for BMDO Sensors. This program will provide flight experiment verification of hybrid active/passive vibration isolation technology and fine pointing control for optics payloads.

Finally there is the Adaptive Neural Controller. Conventional control systems sense the vibration in a structural system and provide feedback to active devices which either change the stiffness of the structure or impart compensating impulses to the structure. The algorithm by which the control system operates is determined by extensive modelling of the structure on the ground. Once the spacecraft is launched the algorithm cannot be changed and if the structure changes in any way the algorithm no longer responds to the structure in an effective way. Adaptive Neural Controllers change the algorithm autonomously with changing conditions. The use of neural networks will also make it unnecessary to do extensive structural modeling and analysis prior to control system design. Also, on-board health monitoring and real-time controller reconfiguration are essential to achieve a higher degree of autonomous behavior. The Adaptive Neural Controller program at Phillips Laboratory will provide experimental verification of an autonomous space platform which uses neural networks within its structural control system.

All Composite Spacecraft Bus Structure. VTS is developing all composite bus technology. In the short term this technology is being applied to the STRV2 satellite. The all composite structure offers a 50% weight and an 80% parts count reduction. It is estimated that a 50% saving in fabrication and assembly time will be realized by going to the all composite bus.

Radiators and Antennas. In addition, the Structures and Controls Division is working on Carbon-Carbon radiators, and composite antennas to improve performance and reduce mass. Carbon-Carbon can save approximately 10% of the antenna weight over conventional Aluminum with no degradation in performance. Composite heat radiators can save up to 50% of the weight of an Aluminum radiator with a higher thermal conductivity that provides more uniform temperature control.

Multi Function Structures. Multifunction structures not only act as load bearing members, but also provide a wire harness by incorporating electronic, power, ground, and data transmission pathways embedded in the spacecraft structure using thick and thin film technologies, to provide adequate shielding and insulation between each layer. This approach would reduce the weight of wiring harnesses eliminating the need for insulation. The technology goal is modular integration of ground planes, power networks, bus and transmission lines into the spacecraft load bearing structure, while designing the electrical pathways to withstand launch and operational environments and to be easily producible. The improved modularity of this approach reduces development, integration and test cost, and schedules.

Space Power Technology:

By the year 2002 we expect that advances in conventional space power should reduce the mass of the electrical power system for satellites by a factor of three. The Phillips Lab Space Power and Thermal Management Division is making several advances that will help us achieve this goal. Some of their programs are described below.

Solar Arrays.

Unfortunately, "solar array masses do not scale down linearly with power, so preventing the power system mass fraction from increasing as satellites are made smaller is a design concern." [1] Work is under way at Phillips Lab and elsewhere to increase the efficiency of solar cells and especially to maintain efficiency as the array size is reduced. Gallium Arsenide arrays have higher efficiency than Silicon, but GaAs arrays have only about 18% efficiency. What is needed for a small satellite is an efficiency in the neighborhood of 25% or greater, especially if power requirements do not go down considerably as satellite size is reduced. Cells of gallium indium phosphide / gallium arsenide /germanium triple junction cells show promise of attaining the required efficiency.

Thin Film Arrays. The benefits of thin film solar arrays are a 30-40% reduction in array

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[1] Gledhill, Lt Kristen and Marvin, Dr Dean *Future Trends in Space Photovolatics*

weight and significant cost reductions over existing arrays. Flexible arrays coupled with shape memory alloys for deployment could provide significant mass and size reductions.

"Channel" Solar Array. This program calls for the development of a high performance solar array called the "Astro-Edge". This array has been chosen for the NASA Small Satellite Technology Initiative (SSTI) Satellite "Clark". The development program calls for a significant improvement in performance over the current state of the art (120 W/Kg Vs 35 W/Kg)

All Back Contact Ultra-Thin GaAs Solar Cell. VTP currently has a program to develop an ultra-thin, lightweight, high-efficiency GaAs solar cell with all back contacts, so there is no obscuration of the incoming sunlight by the contacts. The projected specific power for this idea is about 2000W/Kg at a projected efficiency of 22.5%! These numbers are for the cells themselves and not for an array made from them. If the results of this effort come close to the projections, it will be a large advance for GaAs solar cells.

Batteries.

NaS batteries offer a 50% weight savings over NiH2 and have a potential for a longer life. Phillips Laboratory's Space Power and Thermal Management Division (VTP) is currently performing ground tests (safety and life) on these batteries and expects to flight test them in July '96.

However, the real promise for the future is Lithium ion, or so-called "solid state" batteries. This battery will have double the specific power (about 200 WHr/Kg) of NaS batteries and be extremely low cost. Current projections show this battery being available in the 2002 time frame and, as of now, is considered a high risk development.

Summary Table

Solar Arrays	W/Kg	Eff
GaInP/GaAs/Ge	150	26%
*Ultra-Thin GaAs	2000	22.5%
Thin Film	150	18%
"Channel" Solar Array	120	-----
**SOA GaAs	35	18%

*cell only
** includes support structure

Batteries	WHr/Kg
NiH2	50
NaS	100-150
Li Ion	150- 200

High Voltage Power Management and Distribution (PMAD).

Work currently underway at VTP on high voltage (50V-100V) converters, switches, shunt systems, etc., will reduce the weight and volume of satellite PMAD systems by 50% with greater efficiency than currently available. A high voltage system enables a significant reduction in the mass of the wiring harnesses. In general this technology is applicable to spacecraft with power requirements over one kilowatt. If the total power requirement is under a kilowatt or if there are multiple payloads where the current to each load would be under 3 amps, there is no advantage to higher voltage. Satellite designers won't generally go below 24 gauge wire because of its mechanical properties. Smaller gauge wire tends to have problems surviving launch.

Integrated Power Systems.

The focus of integrated power system research is to incorporate components that would normally be part of the satellite into the solar panels. One effort is to develop an integrated power cell incorporating a solid state battery, a charging circuit, and a solar array. Another effort incorporates a solar cell with a shunt regulation system, removing the regulation system from the spacecraft to the solar panel. Both of these ideas promise to reduce the weight of the power system and thereby the satellite. In addition, these concepts remove wire harnesses and complexity by locating all power components on the array. They also enable the implementation of a modular power subsystem that can meet a range of power requirements. This is important for "common busses" and eliminates substantial bus modifications for different power requirements.

Thermal Management.

Currently there are two primary applications driving thermal management systems, high power density electronics and low temperature infrared sensor satellites. The continual growth in electronics power density creates unique challenges for the thermal subsystem. PL has concentrated on heat pipe design, high conductivity radiators, deployable radiators, flexible heat pipes, and capillary pump loops to meet these stringent requirements.

Many infrared sensors operate at cryogenic temperatures. Currently most FPA's that operate below 100K use expendable cryostats that limit life and result in a substantial mass penalty. Space qualified, long life cryogenic coolers are in development to replace cryostats. VTP is performing extensive characterization testing and integration/flight experiments with cryocoolers. In addition, PL is developing the necessary cryogenic integration components (e.g., thermal storage units)

Spacecraft Electronics.

Computers and digital signal processors have had the most dramatic impact on satellites. Recent estimates show the capabilities of computers and signal processors per unit cost doubling every seven months, while their sizes and costs are continually decreasing. Every time a breakthrough is made in computer speed or capacity it enables a new capability. As mentioned above, computers are even used in smart structures for damping vibrations. Phillips Lab has a number of computer and signal processor programs ongoing, with an emphasis on radiation hardening.

32 Bit Signal and Data Processing The Space Electronics Division of Phillips Laboratory (VTE) is working with LORAL and Honeywell to develop fast, high throughput, lightweight, radiation hardened, space qualifiable computers.

Field Programmable Gate Arrays (FPGA) An FPGA is an integrated circuit consisting of user configurable logic blocks and interconnection "fabric" (a silicon based product with wiring embedded). FPGAs have many uses and can be configured in myriad ways. It is estimated that in the future, FPGAs will be the second most numerous electronic component on a satellite, the first being memory chips. It is also possible to change the programming of the FPGA while in orbit so that one FPGA can perform two or more functions, as long as those functions do not have to be performed simultaneously.

Digital Signal Processors (DSP) VTE has a program to develop a space qualifiable DSP that is hardware, software, and programming compatible with commercially available DSPs

Integration Efforts.

While Phillips Laboratory has made significant strides at reducing the size and weight of space satellites in the areas of individual technologies, we feel that the greatest strides are yet to come, specifically in the area of technology insertion and new concepts that cross the bounds of traditional spacecraft subsystems. Below are several examples which we feel point the way to this new paradigm. Smart design and good integration efforts can produce drastic reductions in the weight of space satellites. The Directorate of Space and Missiles Technology has created the Integrated Technology Development and Demonstration Office (VT-I) which has the responsibility to execute integrated development and demonstration programs. The projects described below have been proposed for ground demonstration within the Integrated Ground Demonstration Lab, (IGDL).

The IGDL has the primary objective of integrating emerging technologies into innovative demonstration systems that can be proven on the ground for a reduced cost. In addition, the IGDL will provide new concepts a conduit into space flight demonstration by teaming with PL/SX, STP, and NASA. The first project to be selected for an integrated demo was the Ultra Lightweight Imaging Technology Experiment (Ultra-LITE)

Ultra-LITE The UltraLITE concepts provide a method for collecting high resolution imagery at a fraction of the mass of a state-of-the-art monolithic telescope. There are two basic approaches - lighter mass monolithic apertures and sparse optical arrays. Both approaches require individual optical segments to be actively controlled or adaptive optics to correct surface errors for wavefront phasing. The current state-of-the-art monolithic apertures are fabricated from ultra low expansion (ULE) glass and are limited in total diameter by production difficulties and cost and by the volumetric constraint of the current fleet of launch vehicles. The UltraLITE concepts address both problems, enabling larger aperture higher resolution systems.

Three monolithic concepts were proposed for UltraLITE. (1) A large aperture SiC primary mirror reduces telescope mass, but is still limited by fairing volumetric constraints. (2) A deployable primary has been proposed for the infrared wavelengths to allow packaging of aperture greater than 2.5 m. However, this system will be heavier than the baseline monolithic for aperture less than 2.5 m. (3) An inflatable primary mirror, in conjunction with adaptive optics, has been proposed to reduce mass and packaging volume.

Three sparse optical array concepts were also proposed for the UltraLITE program. Each of these concepts require precise control between optical elements and image reconstruction algorithms. (1) The multiple telescope concept merges the information of several telescope sub-apertures in the pupil plane to produce the same resolution as a telescope with an aperture diameter that encloses all sub-apertures. (2) The segmented primary aperture essentially removes a large portion of the primary mirror - reducing mass. By only collecting photons over a portion of the aperture, each of these systems lose spatial information. However, if a proper configuration is chosen, all zeros can be removed from the MTF (Modulation Transfer Function). The image can then be reconstructed, amplifying those portions of the MTF that have low gain. (3) The third sparse array concept operates by dynamically filling the aperture, taking several frames of data as the sparse aperture is repositioned. The frames can be added to produce a high resolution image. These systems offer two benefits: a large potential reduction in total telescope mass (if the hardware required to actively control the mirrors and processing data doesn't offset the mirror mass savings) and enables telescope apertures greater than 2.5 m to be stowed and launched in our existing launch vehicles.

<u>Flywheel Energy Storage/Momentum Storage System.</u> This concept uses rotating flywheels as an energy storage device rivaling chemical batteries in power density. Current spacecraft use momentum wheels, reaction wheels or control moment gyros, solely for attitude control. They must be spun-up and de-spun using propellant or torque rods. Current spacecraft also use chemical batteries for electrical power. The flywheel energy/ momentum storage system utilizes the attitude control system for electrical power storage as well, eliminating the need for chemical batteries. Improvements in structural technologies have allowed the rotational speed of flywheels to increase to the point where they can store more energy per kilogram than current chemical batteries. Rotational speeds on the order of 200,000 RPM are possible for such a system. In a typical design, there would be two parallel flywheels each with a motor/generator attached to the shaft. During charging/discharging torque would be applied to each wheel, either from a motor or a generator, in opposite directions. Since the torques are applied in opposite directions, there is zero net momentum change imparted on the spacecraft and the attitude is not affected. Each flywheel would spin at different rates producing the required stabilization momentum vector for spacecraft attitude control. The concept could be extended to apply to a set of reaction wheels or control moment gyros.

<u>ASIM Satellite.</u> The Application Specific Integrated Machine (ASIM) utilizes micro-machining technologies emerging from the digital electronics industry. ASIM satellites could incorporate temperature, pressure, acceleration, etc. sensors and a visible detector onto a single chip along with data processing. The entire satellite would be fabricated on wafers 2-3 " in diameter and a number of wafers (each for a different spacecraft subsystem) would be stacked together to make the spacecraft 1/2-1" thick. The satellite would be powered by solar cells and small batteries. Micro-valves and nozzles could be used to provide attitude control. A communication system, transmitting at 100-1000mW, would downlink the mission data. This "microsatellite" concept has several

possible missions. One potential is to fly it on a larger host satellite. The ASIM satellite could be fitted with a CCD or active pixel CMOS camera and be remotely piloted to check out the hosts deployable components and exterior hardware. In addition the ASIM satellite could serve as a calibration source for an optical payload. ASIM satellites could also be used to perform low resolution monitoring of the earth's environmental conditions or fly in a constellation to make up a phased array or optical system.

<u>MEMS Technology</u> Micro-Electro Mechanical Systems technology has been used to miniaturize a number of electromechanical devices. For instance, entire IMUs have been put on a single chip. By integrating MEMS into a satellite design weight and power reductions can be realized. There are several electronics, networking, digital storage and sensing components that present day MEMS technology could replace. Bus electronics, data storage, and processing could be combined on a single chip. MEMS RF transmitters and receivers could eliminate the need for traditional wiring harnesses for communication and control between the spacecraft controller and components. For example, MEMS could allow the spacecraft controller to command reaction wheel motor speed via a small receiver embedded in the motor drive controller. The same technique could be used with any other components that can not be integrated into a multi-chip module. In the future, MEMS should be capable of integrating the satellite attitude determination and control system (ADACS) into a single package. As stated above, IMUs (with high drift rates) have already been fabricated, earth and sun sensors can be replaced by MEMS sensors with micro-machined optics and the magnetometer can be replaced by MEMS sensing elements. The entire ensemble can be put on a single multi-chip module.[i]

Conclusion. The technologies discussed here will enable a reduction in size of satellites and significantly increase their capability. As small satellites become more capable, they will increasingly take over jobs that were once performed by large satellites. More satellites can be launched on any given launch vehicle thereby reducing launch costs. Small satellites can have the advantage of shorter production times, thereby decreasing cost and schedules.

Integration efforts can achieve significant savings in weight, and realize increases in performance for both large and small satellites. The Phillips Lab IGDL, provides the capability to do ground demonstrations of integrated technologies in an environment that is traceable to a space. This will give us the confidence that a technology will work in space before committing to an operational demonstration.

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[i] Bell, Kevin D. *Application Specific Integrated Micro-Instruments and Micro-electromechanical Systems Technology Insertion Analysis*