MightySat II: On-Orbit Lab Bench for Air Force Research Laboratory

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Abstract. MightySat is a United States Air Force (USAF) multi-mission, small satellite program dedicated to providing rapid, frequent, on-orbit demonstrations of high payoff space system technologies. The Air Force Research Laboratory (AFRL) is the USAF center for space technology research and development. MightySat platforms provide the on-orbit "lab bench" for responsively testing emerging technologies to ensure their readiness for operational Air Force missions. This paper focuses on the MightySat II space vehicle, follow-on to MightySat I (on-orbit from 14 December 1998 to 16 November 1999), which was developed largely by Spectrum Astro, Inc. in Gilbert, Arizona. MightySat II is a 121 kg (266 lb) satellite designed for deployment from the second Orbital/Suborbital Program (OSP), or Minotaur 2 launch vehicle; it completed payload integration and testing (I&T) in May 2000 and launched in July 2000. This paper discusses details of I&T, mission operations, and some lessons learned. Experiments aboard MightySat II include the following: (1) Fourier Transform Hyperspectral Imager (FTHSI), (2) Quad C40 processor (QC40), (3) Shaped Memory Alloy Thermoelastic Tailoring Experiment (SMATTE), (4) PicoSats, (5) Solar Array Concentrator (SAC), (6) Solar Array Flexible Interconnect (SAFI), (7) Naval Research Laboratory Miniature Transponder (NSX), (8) Multi-functional Composite Bus Structure, (9) Solar Array Substrate (SAS), and (10) Starfire Optical Range Optical Reflectors.

Introduction

Some say it looks like a broken television, but this small satellite is packed with enabling technologies for tomorrow's cutting-edge United States Air Force needs. MightySat is a technology demonstration program, directed by the Air Force Research Laboratory (AFRL), Space Vehicles Directorate at Kirtland AFB, New Mexico. MightySat consists of two phases, the first (MightySat I) being a process pathfinder for the second (MightySat II).

MightySat Objectives

The primary mission objectives of the MightySat program are to assist in transitioning advanced space technologies from the laboratory to the warfighter, or operational user, and to demonstrate and provide flight heritage for cutting-edge space vehicle technologies. MightySat fulfills this objective by serving as an on-orbit lab bench to prove these emerging technologies in the space environment. A secondary objective of the program is to accomplish the first objective expeditiously and in a timely manner, such that the technologies are proven and implemented well before they become obsolete. The MightySat program, which consists of a sequence of as many as six satellites, was designed for 18- to 24-month launch centers. A tertiary objective of MightySat is to provide hands-on experience to junior Air Force officers—gaining valuable knowledge in systems engineering, spacecraft and payload design, development, integration and testing (I&T), launch, and mission operations. With this experience, these officers will more effectively be able to make decisions for and otherwise guide future technical and operational space programs.

Background

MightySat I

The first phase of the MightySat program, or MightySat I, was a spin-stabilized, tumbling satellite, weighing 61 kilograms (135 pounds). It was refurbished (from an existing spacecraft bus) and designed for this mission by Orbital Sciences Corporation (OSC), McLean, Virginia (formerly CTA Space Systems). MightySat I was composed of five experiments and was deployed from the Space Shuttle *Endeavor* on 14 December 1998. It was inserted at an altitude of 385 kilometers (208 nautical miles) at an inclination of 51.6 degrees. Its mission completed with re-entry on 16 November 1999, with 100 percent success of all experiments. Its experiments were the Advanced Composite Structure, Advanced Solar Cell Experiment, Microsystems And Packaging for Low-power Electronics (MAPLE-1), Shape Memory Actuated Release Devices (SMARD), and MicroParticle Impact Detector (MPID). Total bill for MightySat I was $7 million; this included spacecraft development and fabrication, payload and spacecraft I&T, launch, and mission operations. For more detail about the experiments and their results, refer to "MightySat I: In Space", Capt B. Braun, 13th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 1999.

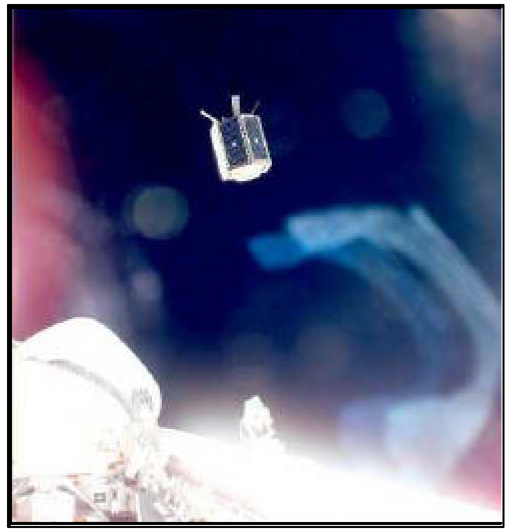

Figure 1. MightySat I deployed from Space Shuttle *Endeavor* (14 Dec 98).

MightySat II

MightySat II is a three-axis stabilized satellite and weighs 121 kilograms (266 pounds). MightySat II launched on 19 July 2000 on the Orbital/Suborbital Program's second launch vehicle. Also known as Minotaur 2, this four-stage launch vehicle was built largely by OSC, Chandler, Arizona, and was comprised of the first two stages of a Minuteman II missile (M55 A1 and SR19 motors) and the second and third stages of the OSC Pegasus launch vehicle

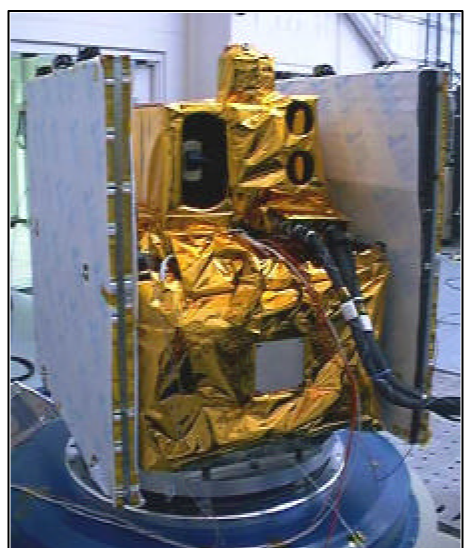

Figure 2. MightySat II ready for flight (May 2000).

(Orion 50XL and Orion 38 motors). Minotaur 2 delivered MightySat II into a circular, sun-synchronous orbit at an altitude of 550 kilometers (297 nautical miles) and at an inclination of 97.6 degrees. Total approximate cost for MightySat II is $20 million ($36.4 million, including launch vehicle, I&T, and mission operations).

Spacecraft Subsystems

Due to the experimental nature of MightySat II, it is termed a Class D satellite, which essentially means that testing requirements are less stringent and that subsystems may be single string (no redundancy). Refer to Table 1 for a summary of MightySat II's specifications.

Attitude Control Subsystem (ACS). MightySat II's ACS is the only subsystem with redundancy, at least functionally. Attitude determination is achieved through a coarse sun sensor, a star tracker, a three-axis magnetometer, and an inertial measurement unit. Three reaction/momentum wheels placed in each axis control spacecraft attitude. Secondary control may be achieved by three electro-magnetic torque rods; these torque rods also serve to dissipate reaction wheel momentum. ACS also autonomously controls solar array articulation for optimum solar energy capture. ACS provides spacecraft knowledge to an accuracy of 0.15 degrees and controls the spacecraft to within 0.18 degrees.

Electrical Power Subsystem (EPS). MightySat II is powered through two sources—batteries and solar cells. There are three batteries, each of which consists of 22 D-size, nickel-cadmium cells. Each battery provides 4 Amp-hours of energy, for a total of 12 Amp-hours. Maximum available power is 330 Watts (beginning of life), though nominal operating levels will be close to 100 Watts. The spacecraft is powered from the batteries during eclipse, while the solar arrays (populated with silicon photovoltaic cells) provide power for the spacecraft and charge the batteries during sunlight. A Charge Control Unit for each battery directs current for powered operations either directly from the four solar array panels (two panels per wing) or from the batteries' electrical storage.

Command and Data Handling (C&DH) Subsystem. Spacecraft C&DH is handled primarily through use of Versa-Module Eurocard (VME) electronics cards (6U form factor), to include a RAD6000 central processing unit, solid-state memory (SSM), attitude control interface, command interface unit, power distribution unit, spacecraft power conversion unit, and experiment power conversion unit. The SSM contains 380 megabytes of available memory, and data transfer occurs at a rate of nearly 23 megabytes per second. These cards are housed in a composite VME cage in the spacecraft interior. Also in the VME cage are the interface electronics for three of MightySat II's stand-alone experiments, as well as for the experimental transponder (transmitter/receiver).

Telemetry, Tracking and Command (TT&C) Subsystem. TT&C is achieved via a miniature transponder unit, which will be discussed later in this section. All spacecraft-ground communication passes through either of the two S-band patch antennae on MightySat II. The pair of patch antennae provides 4π steradian communication coverage for the satellite. The two antennae are connected to the transponder by a 6-decibel coupler and diplexer unit. Ground tracking is accomplished through use of Space-to-Ground Link System (SGLS) ground stations. All uplink and downlink signals are encrypted, though MightySat II data is unclassified. All commanding is uplinked at 20 kilobits per second, and data may be downlinked at either 20 kilobits or 1 megabit per second.

Thermal Control Subsystem (TCS). MightySat II's multi-functional composite structure was designed to facilitate thermal control of the spacecraft. By design, the structure's fibers distribute thermal loading throughout the spacecraft, via thermal spools that dissipate heat to radiator panels. Additionally, the radiator panels, solar panel backs, and launch adapter rings are covered with silver-coated Teflon tape for enhanced emissivity and reflectivity. All other exposed surfaces are covered with 15-layer, gold-colored insulation blanketing. Active thermal control is achieved by monitoring temperatures and operationally adjusting component and payload on-times accordingly. Payload operating temperatures are designed to fall between -20° and +20° C.

Structures and Mechanisms. MightySat II is founded on a multi-functional composite bus structure, as previously mentioned. It will be discussed in greater detail later in this section. In its stowed configuration, the satellite measures 34.13 inches high by 34.88 inches deep by 26.62 inches wide. (See Figure 3.) With solar wings deployed, the satellite measures 170.18 inches wide. (See Figure 4.)

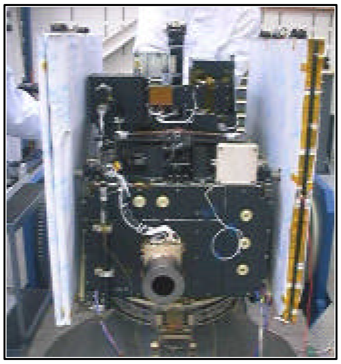

Figure 3. Stowed Configuration

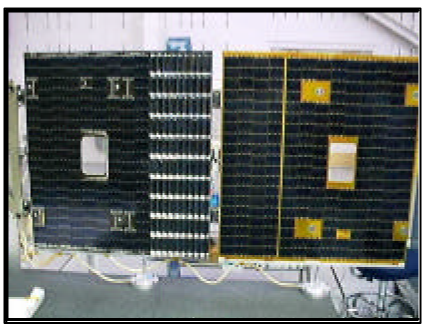

Figure 4. Deployed Wing

MightySat II contains four mechanized assemblies. One is the PicoSats launcher assembly, which will be discussed later in this section. The second consists of Solar Array Release Mechanisms (SARMs) and solar array hinges and dampers for array deployment following orbit insertion. The eight SARMs (four for each solar array wing) "fire" autonomously once the ACS system has acquired and points the spacecraft toward the sun. This "firing" is accomplished with heated-paraffin actuators, which allow for the release of a constraining cable. Once the arrays release, the spring-loaded hinges deploy the solar array wings, while being rate-controlled by dampers. The third mechanism is the solar array drive assembly. Each of these two assemblies consists of two motors, which give the arrays two-dimensional articulation. MightySat II's fourth mechanism consists of two separation switches, which are attached to the base of the launch adapter ring. In its launch configuration, the plunger-type switches are depressed or closed; once the space vehicle separates from the launch vehicle, the plungers extend or open, and the spacecraft initiates its boot sequence.

Table 1. MightySat II Specifications Summary

General	
Orbit	550 km (297 nmi) circular, sun-synch 97.6° inclination
Mass	121 kg (266 lbs)
Dimensions – stowed -- deployed	34.13 x 34.88 x 26.62 in. 170.18 in. wide
Launch Vehicle	Minotaur 2, 4 stages
ACS	
Stabilization	3-axis
Inertial Knowledge	0.15°
Inertial Control	0.18°
EPS	
Total Power	330 W (BOL)
Nominal Power	100 W
Bus Voltage	28 ± 6 V
Secondary Voltages	± 15 ± 0.3 V ± 5 ± 0.1 V
Solar Arrays	2-D articulation
C&DH	
Electronics/Avionics	16-bit, 6U VME
CPU	RAD6000
Solid State Memory	380 MB
Data Transfer	~ 23 MBps
TT&C	
Uplink	20 kbps
Downlink	20 kbps or 1 Mbps
Antennae	S-band, patch 4π steradian coverage
Tracking	SGLS, ± 1 km

Stand-Alone Experiments

MightySat II has a total of 10 experiments, five of which are independent of the spacecraft bus or stand-alone, and five of which are experimental bus components.

Fourier Transform Hyperspectral Imager (FTHSI). FTHSI is MightySat II's primary payload. Its objective is to evaluate the performance of space-based Fourier transform interferometer technology for the hyperspectral imager (HSI). FTHSI is the only Department of Defense space-based HSI to use state-of-the-art Fourier Transform technique and may provide improvement over traditional dispersive- or grating-type sensors, particularly for long-wave infrared applications. This instrument may also provide the means to detect and identify military targets, despite camouflage or other concealment, categorize terrain, and assess trafficability for ground troop movement. Commercial applications include classification of environmental/crop damage and many others.

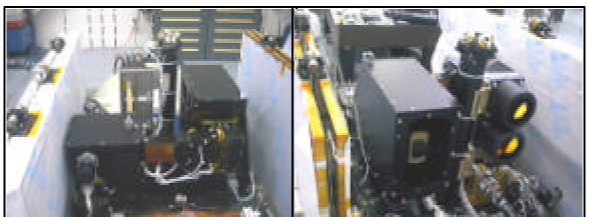

Figure 5. FTHSI: left-camera, lenses; right-telescope.

During its one-year life, FTHSI may collect as many as 200 to 300 images. These images may help to evaluate the utility of Fourier Transform technology for earth remote sensing missions and will be compared with grating-type HSI.

The FTHSI camera has a 1024 x 1024 pixel charge-couple device and a 15-centimeter aperture. It weighs 20 kilograms (44 pounds), has a volume of 18,000 cm^3, and consumes a maximum of 51 Watts during operation. The imager operates in a waveband of 470 - 1050 nanometers, has 28-meter spatial resolution, 3-degree field of view, and a nominal swath size of 15 x 20 kilometers. Spectral resolution is 86 cm^{-1} (1.7 nanometers at 870 km orbit and 9.7 nanometers at 1945 km), which covers about 150 spectral bands. Nominal image data size is 256 megabytes, which requires less than 22 seconds to collect.

Placed between the mirror telescope and camera, in the L-shaped train, FTHSI uses a Sagnac common-path interferometer. In this design, the instrument has no mechanical actuation of mirrors or lenses, making FTHSI quite robust. Imaging then is accomplished through commands to and maneuvering from the spacecraft ACS and commands to the FTHSI interface (HII) board in the VME cage. HII commands consist of camera and data acquisition settings. Acquired image data are transferred directly to the SSM in blocks of 24,500 bytes. Hundreds of these blocks may be downlinked during each pass that MightySat II makes over a ground station; following multiple passes, the complete set of data is assembled and processed. Another option for the data is on-board processing, which is accomplished by transferring the data from the SSM to the synergistic experiment, Quad C40 processor (also in the VME cage). This processor will be discussed in the next subsection.

Scientific reasoning for FTHSI on MightySat II includes the need to space-qualify this technology. Of particular importance are the observations of Earth surface features through the entire atmosphere. Since FTHSI depends on solar illumination of Earth's surface for signature, the contribution of Earth's atmosphere plays an important role in the ultimate signature recorded by the sensor. By contrast, in an aircraft, only one half of the total propagation path can be realized. Only in space can an imager "see" the full effect of the atmosphere. Another reason for this space demonstration is to seek to account for the effects of orbital velocity on FTHSI's ability to collect meaningful data.

Quad C40 Processor (QC40). QC40 consists of two VME cards. One board is comprised of four commercial, off-the-shelf (COTS) TMS320C40 microprocessors, while the other board provides the interface between the processor board and the remaining spacecraft electronics. QC40 weighs 1.4 kilograms (3.1 pounds), consumes 17 Watts during operation, and processes at 120 megaflop (floating point operations per second). An initial objective was to space-qualify a radiation-hardened QC40, but following several ground radiation tests, where no degradation occurred at levels as high as 300 kilorad (payload specification was only 25 kilorad), radiation shielding was deemed unnecessary for this mission. The MightySat mission should prove QC40's other significant objectives, which are specific to FTHSI data handling.

QC40 allows for on-board conversion of the interferogram to spectral data, which normally takes place during ground processing. QC40 also compresses data and during I&T proved its ability to reduce the maximum image collection size from 256 megabytes to 70 megabytes. QC40 also performs feature and real-time centerburst extractions. Feature extraction involves comparing and matching collected interferograms with on-board interferograms of known materials. Real-time centerburst extraction allows ground operators to obtain a quick-look of the collected image to assess whether it's worthy of devoting several downlinks to accrue all of the data; for example, if numerous clouds obstruct the image, the data may not be downloaded.

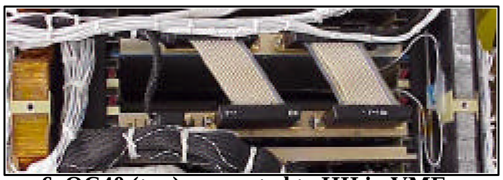

Figure 6. QC40 (top) connected to HII in VME cage.

Shape Memory Alloy Thermoelastic Tailoring Experiment (SMATTE). Shape memory alloys have the inherent ability to "remember" a specific memorized or pre-formed shape. When the material is heated above its transition temperature, it returns to its memorized shape. SMATTE consists of a layer of polymer matrix composite with a thin strip of shape memory alloy both atop and beneath and of an accompanying interface electronics board in the VME cage. Maximum power draw is 5.3 Watts during operation.

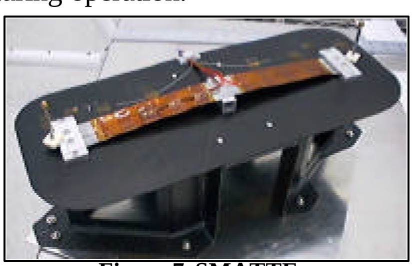

Figure 7. SMATTE

Stress induced from thermal warping of the composite will be autonomously relieved by opposing stress in the shape memory alloy film. Optical fiber strain gauges monitor SMATTE's performance. SMATTE will pathfind the ability in larger space-based composite structures to autonomously control deformation for overcoming thermally induced stresses. It also has potential application for shaping composite antennae.

PicoSats. This experiment consists of two picosatellites, which are tethered together, and a spring-loaded automated launcher assembly. Toward the end of MightySat II's mission, these PicoSats will be deployed from the bottom side of the space vehicle. Each PicoSat measures roughly 10 x 8 x 3 centimeters and weighs less than 230 grams (0.5 pounds). Once released, the PicoSats will transmit a low-power beacon to a large ground radar dish. The tether contains gold strands for easier tracking. Each PicoSat also contains Micro Electro-Mechanical Systems (MEMS) radio frequency switches for transmitting data. This MEMS technology is an upgraded version from the first PicoSats deployment (OPAL satellite, Feb 00).

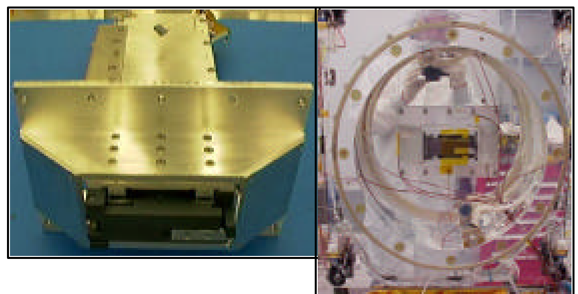

Figure 8. PicoSats launch from base of MightySat II.

The non-explosive PicoSats Launcher Assembly (PLA) ejects the PicoSats via a spring assembly, contained by a deployable door. The main ejection spring, which is loaded to a force of 1.9 lb_f, will eject the PicoSats at a rate of 1 foot per second. The PicoSat-to-PicoSat separator spring is loaded to 0.25 lb_f. The PLA mechanism is activated by the heating and melting of a resistor/fuse which allows unwinding of a bolt-and-catch mechanism. Once deployed, the door remains open for the duration of the spacecraft's mission.

Starfire Optical Range (SOR) Optical Reflectors. Two COTS optical reflector mirrors are affixed to the coarse sensor boom on the spacecraft top deck. They are further reinforced by an aluminum bracket fastened to the top deck. Together, the reflectors weigh 1.76 kilograms (3.88 pounds) and are entirely passive. The SOR, based at Kirtland AFB, New Mexico, will perform active ranging of MightySat

II's position via ground-based laser, to better understand atmospheric effects on laser tracking.

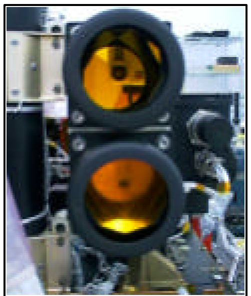

Figure 9. Optical Reflectors

Experimental Bus Components

In addition to MightySat II's Stand-Alone Experiments, several spacecraft bus components demonstrate technologies for improving satellite performance and efficiency.

Solar Array Concentrator (SAC). The SAC covers one-third of one of the four solar panels on MightySat II. With roughly one-third the number of photovoltaic cells—albeit these cells are gallium arsenide with 22 - 24 percent efficiency vice the silicon cells with 17 - 19 percent—this string of cells generates the same amount of power as each of the other strings. The SAC provides a concentration ratio of 3-to-1 and has a 20-degree pointing tolerance toward the sun. With fewer cells, this portion of the panel costs one-half the equivalent silicon-cell panel and weighs the same, or 0.74 kilograms (1.64 pounds). The SAC generates 37 Watts at beginning of life and 27.5 Watts at end of life. MightySat's objectives for the SAC are to prove its performance and its durability in the harsh space environment.

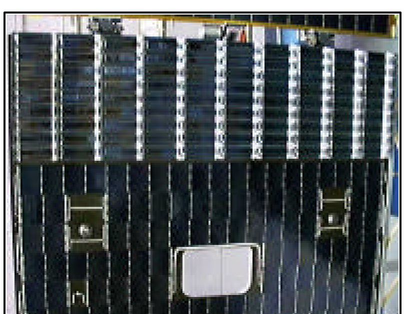

Figure 10. Solar Array Concentrator

Solar Array Flexible Interconnect (SAFI). SAFI is composed of adhesiveless, flexible copper strands embedded in polyimide, and it connects the solar cells and routes the current off the panel. Compared with traditional round-wire cabling, SAFI enables easier integration and assembly, has less mass, and allows increased reliability by elimination of potential fatigue failures of round wires and solder joints. SAFI is bonded to the solar panel with flight-proven pressure-sensitive adhesives and is less than 0.25 millimeters (0.01 inches) thick. SAFI is the "next step" toward a fully multi-functional bus structure, where the wiring is incorporated into the structure. This would allow significant savings in volume, weight, and complexity from what is typically associated with spacecraft wiring/cabling/harnessing.

Solar Array Substrate (SAS). One of MightySat II's four solar panels is a lightweight, graphite-composite, modular orthogrid substrate. It weighs 1.08 kilograms (2.37 pounds) and has specifically designed, excellent thermal management properties.

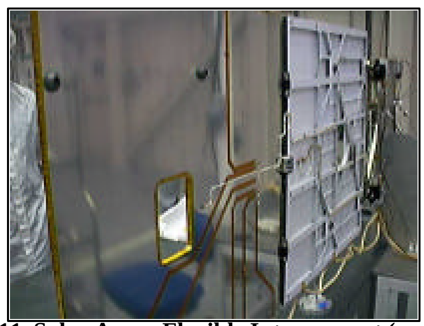

Figure 11. Solar Array Flexible Interconnect (near). Solar Array Substrate (far)

Naval Research Laboratory Miniature Transponder (NSX). NSX's fundamental objective is to prove the functionality of this newly developed miniature transponder. NSX weighs 1.5 kilograms (3.3 pounds) and measures 5.7 x 5.7 x 2.8 inches, about one-third the mass and volume of a comparable, traditional transponder. NSX allows for use of the Air Force Satellite Control Network for the spacecraft's TT&C. It consists of three segments—Communications Security (COMSEC), transmitter, and receiver—and is located snugly in the VME cage. It features an encryptor and decryptor in the COMSEC segment, magnesium housings, miniature ceramic filters, surface-mount technology devices, hybridized power supplies, hybridized interference/baseband circuitry, hybridized RF-modulator, and digital implementation of tone detection and bit synchronous circuitry. It requires 6 Watts during receive mode and 23.2 Watts during transmit/receive mode. Other details of the NSX were discussed in the TT&C subsection above.

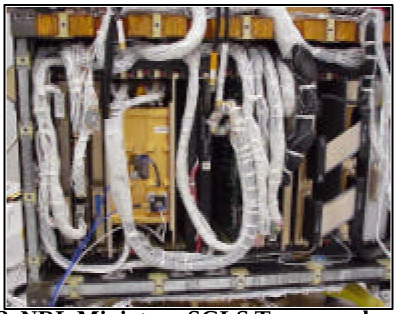

Figure 12. NRL Miniature SGLS Transponder (NSX) in VME cage (gold-color toward left).

Multi-functional Composite Bus Structure. The 30-pound spacecraft structure is manufactured from 1.6-pound core aluminum honeycomb between face-sheets of either 0.050- or 0.020-inch thick M55J graphite, cyanate-esther composite. The structure is further constructed using M800 graphite, cyanate-esther composite thermal radiators tied to spacecraft components through aluminum thermal spools, as discussed earlier. The Multi-functional Composite Structure is specifically designed to tailor both structural and thermal properties of its materials into a high density, rigid structure capable of excelling in launch vehicle dynamic environments, while maximizing thermal throughput to spacecraft radiators. Both a flight model structure and an identical Developmental Test Vehicle (DTV) were manufactured to minimize risk in spacecraft development and to allow AFRL to conduct exhaustive environmental stress screening of this new composite spacecraft bus design.

Experimental value of developing the multifunctional structure includes the demonstration of how composite materials can lower complexity associated with use of external thermal control mechanisms in more traditional all-aluminum honeycomb spacecraft. Additionally, composite structures have shown great promise in creating structures stiffer and lighter than more traditional all-metal frames. The use of composite "snap-set" technology demonstrates the promise of easily manufactured composite structures using standard, readily available composite sheet materials.

The structure incorporates Spectrum Astro's spacecraft design, utilizing a 6U VME card cage completely made of composite material in order to make MightySat a dense, thermally robust, versatile and flexible spacecraft platform by virtue of the VME card protocol.

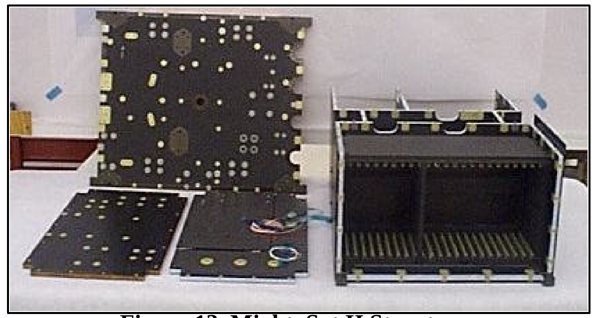

Figure 13. MightySat II Structure

Integration and Testing (I&T)

Spectrum Astro, Inc., performed integration and testing of the MightySat II spacecraft, complete with all of its subsystems. AFRL and its small business contractors performed testing for each payload/experiment. All of the payload integration and space vehicle (spacecraft with payloads) testing occurred at the Aerospace Engineering Facility (AEF), Kirtland AFB, New Mexico, under the combined effort of AFRL and Jackson & Tull (J&T), with additional participation and support provided by Spectrum Astro and the Aerospace Corporation. In addition to the system-level I&T, AFRL and J&T performed component-level testing on the FTHSI and the Multi-functional Composite Bus Structure. This section of the paper focuses on space vehicle I&T and issues related to the experiments, thus excluding spacecraft I&T efforts. All spacecraft components were environmentally and functionally tested prior to delivery of the spacecraft to AFRL in February 1999. Environmentally tested payloads were delivered to AFRL prior to the conclusion of 1999. Figure 14 shows the flow of testing for MightySat II.

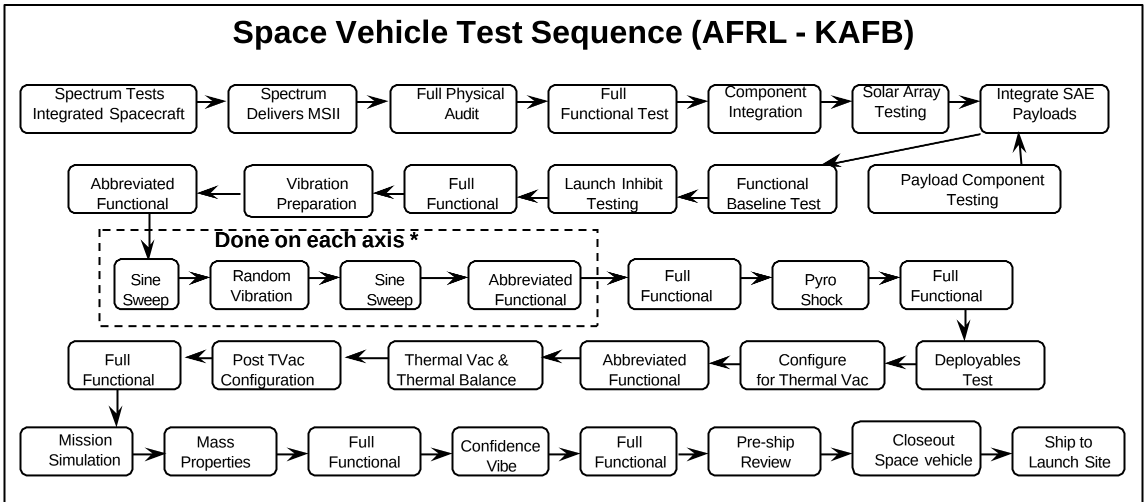

Figure 14. Spacecraft/Space Vehicle Test Flow.

Over the course of 15 months of I&T at the AEF, 173 problems or failures were discovered and corrected/repaired. The major objective of I&T is to find discrepancies in workmanship and performance before the space vehicle becomes inaccessible on orbit. To that end, MightySat I&T efforts were highly successful. The next two subsections, Experimental Bus Components and Stand-Alone Experiments, discuss testing efforts and related fixes, which occurred prior to system-level environmental testing. Then system-level testing and its results are discussed.

Experimental Bus Components

Originally, there were two flight structures, one serving as a flight spare; however, the first structure became the engineering unit, or Developmental Test Vehicle (DTV), after an unexplainable shift in its natural frequency during vibration testing. Both the DTV and flight structure underwent extensive environmental stress screening, per qualification levels prescribed by Mil-Std 1540B. Such tests included multiple 3-axis sine sweeps, random vibration and sine-burst testing with high-fidelity spacecraft component and payload mass simulators and the launch vehicle marmon band adapter ring. Vibration levels reached 15.7 g_{rms}, or 40 percent higher than the expected vibration profile for launch. Thermal cycling and fully instrumented thermal vacuum testing demonstrated that the thermal management abilities of the structure were better than those modeled. To further mitigate risks, thermal modeling of the structure's design was fully replicated by the Aerospace Corporation to ensure adequate margins in this largely untried, combined thermal/structural spacecraft bus. The DTV structure was later used for six additional tests—as the environmental mockup of the spacecraft for the successful, independent laboratory acoustic vibration testing of MightySat II's solar array, SAFI and SAC experiments (3 tests); as a geometric mockup for radio frequency antenna pattern testing; to test the complex, system-level thermal vacuum setup and to mitigate risk to the space vehicle for thermal vacuum testing; and qualify, under proto-qualification vibration loads, a support bracket for the late-comer Optical Reflectors.

As a result of vibration testing of the DTV, loaded with mass simulators, the I&T team found that one of the spacecraft panels was transmitting excessive excitation of two ACS components—the star tracker and inertial measurement unit. To resolve this issue, a piece of composite/aluminum honeycomb panel was affixed to the interior of the "defective" panel, via visco-elastic membrane (VEM) adhesive. (See Figure 15.) This served to dampen, or absorb excess energy from, the transmitted vibrational energy.

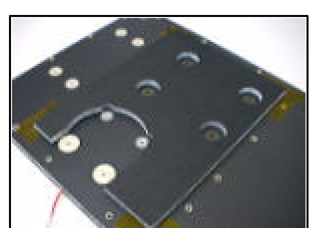

Figure 15. VEM fix to flight structure panel.

Also during DTV vibration testing, with mass models for the Optical Reflectors, the cantilevered weight resulted in a crack and de-bonded inserts in the top deck. In this instance, the DTV again served as a pathfinder for the fortification of the flight structure top deck, to accommodate the actual Optical Reflectors.

After the solar arrays (which include three experiments—SAC, SAFI, and SAS) were delivered to AFRL, technicians and engineers at the AEF performed illumination and deployment testing on them. Illumination testing utilized a combination of high-power xenon and halogen lamps to simulate solar lighting and heating. This test served to verify workmanship of the solar cells' application and wiring to the panels, as well as actual beginning-of-life current and voltage values to confirm predicted values. J&T and AFRL personnel then exercised ingenuity and "MacGyver"-like engineering skill to develop a solar array deployment test that superseded any need to perform it in a thermal vacuum chamber. With the solar array wing resting on air bearings atop a flat, granite table and affixed by its yoke to a SADA- and SARMs-simulator setup, deployment was performed in ambient conditions repeatedly to verify the hinges and dampers. The team then executed more rigorous environmental testing by applying liquid nitrogen then heated-air guns to bring the dampers and hinges/springs to -51°C and +70°C, respectively. This was a challenging test to perform, as the operators had to pay particular attention to not create condensation or excessive temperature gradients on the solar cells, to provide even cooling/heating to all six locations of dampers and hinges, and to maintain the air bearings (which could be impinged by a small particle of dust or debris on the table) and other apparati (which were continually cycled through extreme temperatures) for multiple test runs. As a result of this testing, the team discovered that springs with a higher spring constant or greater force were required for increased confidence in successful on-orbit array deployment.

For the experimental transponder (NSX), AFRL and J&T, in concert with NRL and Space and Missile Systems Center (SMC) personnel, performed a series of transponder-to-ground compatibility tests. During these tests, the team found a deficiency in the transponder's ability to transmit in low rate mode, or 20 kilobits per second, where an unacceptable number of dropouts were occurring. After troubleshooting, the team discerned the problem, the faulty Field-Programmable Gate Array was replaced, and the problem did not recur. During physical integration of the NSX, J&T technicians encountered difficulty in "making it fit" into its allocated space in the VME cage. Typically, the transponder is externally mounted to a spacecraft, but to conserve external real estate for other experiments, the NSX was designed to occupy three card slots in the VME cage. The NSX cable harness, however, was too bulky to allow it to fit in the card cage, so these technicians modified, redressed, and rerouted the harness.

As part of the NSX testing and troubleshooting, the I&T team discovered the need to modify the National Security Agency's ground cryptographic unit, KI-17, which is part of MightySat II's ground support equipment. Again exercising commendable ingenuity and technical expertise, they incorporated a hard-wired work-around to enable error-free communications. This modification will certainly benefit numerous other programs throughout the Department of Defense.

Stand-Alone Experiments

MightySat II's primary instrument, FTHSI, was environmentally tested at the AEF. Vibration and thermal vacuum testing revealed fundamental flaws in its design and assembly. The camera housing required redesign to accommodate the pressure differential between its 1.1 atmosphere (roughly 16

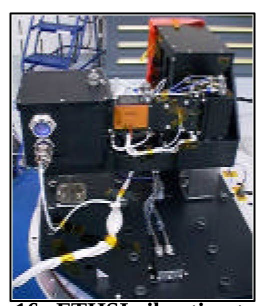

Figure 16. FTHSI vibration testing

pounds per square inch) charge and the vacuum in space. A redesign and refabrication ensued, then the instrument was retested, and there were no further environmental issues. Following some cursory functional checkouts, the team observed less than nominal capability in the camera. After troubleshooting, they learned that a flexible, multiple-lead harness had been pinched upon installation. J&T technicians built a new connector and carefully installed it, prior to retesting.

For operational/functional testing of the FTHSI, AFRL implemented the PERL programming language, which is similar to C+. This language is the vessel by which spacecraft/payload commands are sent and telemetry is collected. With this programming language, AFRL and J&T personnel were able to not only generate qualifying tests for FTHSI, but also to modify space vehicle functional tests—to accommodate variations from initial performance predictions of spacecraft components and payloads. After reviewing image data generated by this FTHSI functional testing, the team observed image inversion, which led to identification and correction of an inverted optical slit piece in front of the lens train assembly.

As mentioned earlier, by performing several iterations of board-level radiation testing of the QC40, engineers and management assessed that pursuit of a radiation-hardened QC40 for MightySat II to demonstrate was not monetarily feasible. Tantalum radiation shielding was considered but ruled out as well, since the board's survivability exceeded requirements for expected radiation total dose. I&T issues for QC40 consisted primarily of software troubleshooting and redesign. Following tests of the initially delivered QC40 software, AFRL essentially rewrote all of the code, to include the interface code between QC40 and HII (FTHSI electronics). Because of locally managed data configuration, the team was able to continue QC40 software modifications and improvements until the baseline functional checkout of the space vehicle, prior to commencing system-level environmental testing.

The PicoSats integration is discussed in detail in the lessons learned section of this paper.

System-Level Environmental Testing

System-level environmental testing, or stress screening, consisted basically of five tests or activities: vibration, separation and pyrotechnic shock, thermal balance and thermal vacuum, mass properties, and confidence vibration. Before and after each of these five tests or activities, the space vehicle underwent full functional testing, which exercised all component and payload relays, functions, and some simulated on-orbit activities. Again, all testing was performed in the AEF at Kirtland AFB.

Vibration testing was performed in all three space vehicle axes on a Ling 4022LX vibration table. The space vehicle was comprised of the spacecraft bus, solar array wings, and all 10 experiments. However, it was not in final flight configuration, as thermal blankets, thermal tape, and ballast mass were not intended to be incorporated for this testing. The PicoSats Launcher Assembly was in place, but the picosatellites were replaced with mass simulators (since the picosatellites were still being refurbished after their early release—discussed later, in "Some Lessons Learned" section of this paper). Thirty-two

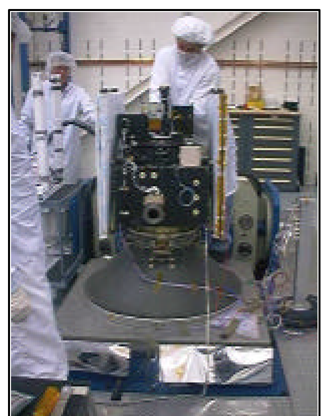

Figure 17. Random vibration testing

accelerometers were placed among MightySat II components, payloads, and structural locations. Random vibration targeted proto-qualification levels, per Mil-Std 1540B, that is, a level 25 percent greater in magnitude than the expected launch vibration profile. In addition to full random vibration testing in each axis, the space vehicle was subjected to pre- and post-sinusoidal sweeps (merely 0.5 g acceleration). The I&T team used these sine sweeps to assess whether any damage resulted from the random vibration. Prior to this system-level random vibration testing, OSP provided launch environment data from the first Minotaur launch in January 2000; these data were implemented in the vibration profile for this test. As a result, the team gained much greater confidence that the space vehicle was tested to an accurate level with sufficient margin of safety. Testing completed successfully with no issues or modifications required.

Following random vibration testing, the I&T team performed pyrotechnic shock and separation testing. Prior to this test, OSC had performed a similar shock test, using the DTV with mass simulators, to verify their newly designed conical adapter (between 17.75-inch space vehicle and 38-inch launch vehicle interfaces). The shock acceleration is the result of firing the pyrotechnic bolt cutters in the marmon band. Results of that test showed instantaneous acceleration levels as great as 500 g. This raised concern over the space vehicle separation switches, which were rated only to a 100-g shock level. During launch, these two separation switches remain in a closed position; after release from the fourth stage of the launch vehicle, the switches open and the space vehicle activates. To mitigate this potential for failure, J&T technicians performed drop testing on the switches. The engineering unit switches did not functionally fail until the instantaneous acceleration level exceeded 1000 g. The flight separation switches were then qualified with 10 shocks in each axis, where the shock level was between 600 and 800 g.

For the system-level pyro-shock test, MightySat II, with conical adapter attached, was suspended from an overhead crane. Pyrotechnic operators fired the bolt cutters, the conical adapter dropped onto electro-static-discharge-safe padding, the separation switches opened, and the spacecraft booted. This test also was a complete success and required no modifications to the space vehicle.

As mentioned previously, two risk-mitigating thermal tests using the DTV were completed prior to space vehicle thermal vacuum testing. These tests allowed for further characterization of the spacecraft bus' thermal paths and heat transfer, which the Spectrum Astro thermal engineer fed into the standing space vehicle thermal models. They also allowed for electro-mechanical verification of and thermal characterization of the test setup—primarily of the solar and albedo (earth) simulators. Each of these two pathfinder tests reduced thermal testing risk to the $20 million space vehicle. Also prior to this test, the space vehicle was covered with thermal blankets and silver-coated Teflon tape, in the locations detailed in the spacecraft TCS subsection of this paper.

The I&T team used an XL Systems Thermal Vacuum Testing Chamber for testing MightySat II. The chamber has an internal diameter of 5 feet and a depth of 9 feet. It has gross-vacuum and cryogenic pumps, capable of 1×10^{-7} Torr (9.7×10^{-9} pounds per square inch), though it dwelled closer to 1×10^{-6} Torr during testing, due to impurities, outgassing, and thermal mass in the chamber. Gaseous or liquid nitrogen may be flowed through the chamber shroud for cooling. During this test, liquid nitrogen was used to achieve an internal chamber temperature of -196°C to simulate deep space.

Figure 18. Thermal vacuum testing

Setup for the thermal vacuum testing was comprised of the space vehicle (without solar arrays) suspended from the ceiling of the chamber and surrounded by the following: a star-field simulator for the star camera, a white-light source for the FTHSI imaging operations, a blanketed aluminum plate with heaters to simulate albedo heating, three banks of halogen lamps to simulate solar and albedo heating on three sides of the space vehicle, and a thermal vacuum-qualified color video camera. These banks of halogen lamps, or sun cages, were connected to a controller and programmed to cycle in a manner to simulate sunlight and eclipse of each orbit. They were also used to heat the space vehicle to component/payload thermal acceptance limits during hot thermal balance and hot mission simulation phases.

The 24-hour testing lasted two weeks (300 testing hours in the thermal vacuum chamber), with a two-day break for modifications toward the end. Testing included a total of five thermal cycles, running at hot and cold acceptance limits. The first cycle lasted one week and included hot and cold thermal balance (where operators/engineers thermally stabilize the space vehicle in hot and cold extremes, for more accurate data to feed into the thermal control model), hot and cold starts (where the space vehicle initializes with components at hot or cold limits), abbreviated functional testing, and mission simulation in hot and cold operating extremes. Each of these mission simulations lasted nearly 48 hours, and included nominal space vehicle operations, beginning from orbital insertion. The next two cycles included abbreviated functional tests at hot and cold for each and during ramp to hot and ramp to cold; they also included abbreviated mission simulations for eight hours each at hot and cold. At that point, the team returned the chamber and space vehicle to ambient temperature and pressure and removed MightySat II for repairs, as a result of some anomalous behavior.

During the first cold soak, the star camera heater thermostat did not operate. During the cold mission simulation, SMATTE's electronics did not function properly. The third problem involved QC40, where it experienced intermittent malfunctioning during the second and third thermal cycles. After the satellite was removed, the I&T team was able to troubleshoot, repair, and verify the repairs for these three failures within two days. The star camera thermostat needed two wires to be reversed, and QC40 and SMATTE electronics boards each required additional resistors. After the modifications/repairs, MightySat was replaced in the chamber and continued for two more thermal cycles, with a total of four more abbreviated functional tests.

Following thermal vacuum testing, MightySat II solar arrays were re-installed, and the I&T team placed it on a moment-of-inertia table to determine its final mass, centers of gravity in each axis, and moments of inertia in each axis. To force the space vehicle to fall within design parameters, about 10 pounds of brass ballast were added. These properties were then inserted into the ACS software for attitude control and submitted to launch vehicle engineers for launch control.

Figure 19. Confidence vibration testing

Confidence vibration was the final, formal environmental test on MightySat II prior to shipment to the launch site. This test consisted of random vibration testing in each of the three axes, with sine sweeps between each axis vibration. Vibration was set to acceptance levels, per Mil-Std 1540B, or to the level expected during launch. By definition, however, all spacecraft components, payloads and the structure were designed to at least a 20 percent margin above expected loads during launch. After shipment to the launch vehicle integration facility at Vandenberg AFB, the I&T team again performed a full functional checkout of the space vehicle, then attached it to the fourth stage of Minotaur 2, where it waited until launch. In the interim, operators performed occasional relay verification tests and battery charging until the day of launch.

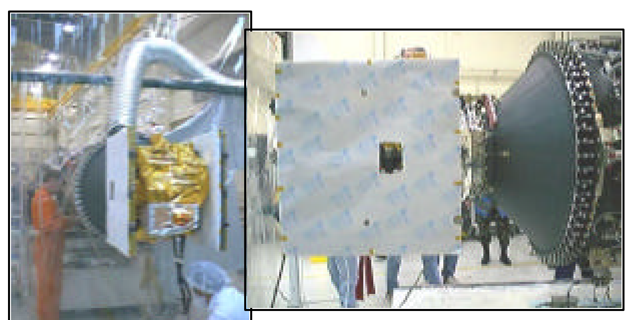

Figure 20. MightySat II attached to 4th stage of Minotaur 2.

Advantages of MightySat I&T Methods

Due to MightySat II's limited personnel and resources, the I&T team developed efficient ways to operate in the AEF. Following are several of the advantages exhibited by the MightySat II I&T methods. The AEF has a high bay, which contains a secure cleanroom, several vibration tables, several thermal and thermal vacuum chambers, electrical room, mechanical room, and a machine shop. With all of this capability contained within one facility, fewer people (who generate less paperwork and "red tape") could accomplish nearly every modification, rework or repair on MightySat II, within an extremely reasonable turn-around time. The AEF and MightySat program office are separated by perhaps 50 meters; this proximity greatly facilitated AFRL personnel interaction with I&T and allowed for immediate progress/problem updates. Another advantage was the I&T team's use of the MightySat Integrated Testbed (MIT). The MIT consists of a VME cage with breakout boxes; the VME cage contains engineering replicas of everything that is in the actual spacecraft avionics, including payload electronics (QC40, SMATTE board, and HII). Attached to the HII and QC40 boards is an FTHSI camera simulator, and attached to the attitude control interface is a high-fidelity ACS subsystem simulator. The MIT proved extremely useful for verification of flight software modifications and of testing program scripts, for testing and troubleshooting the payloads (both engineering and flight units), and for mission operations rehearsals (as a T-1 ground link was established between the MIT and the ground control station—also at Kirtland AFB). By using this link, the operations team gained tremendous confidence in their procedures and ability to "fly" the space vehicle—which they actually accomplished during thermal vacuum testing, for example. This enabled unparalleled opportunity for the control station personnel to exercise and test their requisite ground systems and to realistically rehearse their extensive operations personnel, tools and protocols. The last significant advantage of this sort of I&T effort is the tremendous, invaluable hands-on experience gained by junior officers—lieutenants and captains—on the MightySat II program. They took full advantage of nearly daily interaction in the design, development, and I&T process. Their experience will almost certainly benefit future space and space-related programs, perhaps helping the Air Force to do things smarter, better, and for less money.

Mission Operations

MightySat II mission operations occur at the Research, Development, Test & Evaluation Support Center (RSC), satellite control facility, located at Kirtland AFB, New Mexico. The RSC, operated by SMC's Test & Evaluation Directorate (SMC/TE), is responsible for day-to-day operations of the MightySat vehicle from launch to end of operations. Operations include initial acquisition of the MightySat vehicle, performing commanding, ranging, and tracking of the vehicle, and downloading state of health and payload data. Also, the RSC will perform data processing and data publishing for the experimenters to retrieve.

Phases of Operations

MightySat II operations will occur in three phases. Phase I of operations is the Launch and Early Orbit Operations (LEO) phase. This phase begins when the spacecraft launches and is separated from the launch vehicle. The phase ends when all payload and spacecraft activities are checked out and verified. Activities that occur during Phase I include space vehicle and experiment initialization, spacecraft diagnostics, and validation of the vehicle electronics, EPS, ACS, C&DH, TT&C, and TCS.

Phase II operations begin upon completion of LEO activities. Activities in Phase II consist of FTHSI performance evaluation and normal operations for SMATTE, QC40, experimental bus components, and daily space vehicle maintenance. Phase II will continue from the end of LEO for one month. During this time, all vehicle and experiment activities will be executed out of the Stored Program Commands (SPC) queues. SMATTE and QC40 will perform normal mission operations during this period. FTHSI will perform two types of activities: raw data calibrations (through the SSM) and post-processed data activities (through QC40).

Phase III characterizes the nominal operations portion of the MightySat mission. Operations consist of daily vehicle maintenance activities, experimental bus components operations, and QC40 and SMATTE operations, similar to Phase II. All vehicle and experiment activities will occur out of SPC queues. FTHSI will conclude a performance evaluation at the end of Phase II and will perform a majority of post-processed data collection activities, with some raw data collections occurring as well. This split of FTHSI activities will be 70% post-processed and 30% raw data activities. Lastly, the PicoSats will be ejected towards the end of the mission.

MightySat Mission Operations Team

The mission operations team is a diverse and multi-organizational team, spanning industry, laboratory, contractor, and military personnel from many functional areas. The MightySat program office (MSPO) acts as program managers for the mission. The primary bus contractor, Spectrum Astro, aids the MSPO in diagnosing space vehicle issues and performing routine maintenance activities. The SMC/TE Operations division (SMC/TEO) personnel act as the mission operators. Finally, AFRL personnel collect instrument data and report the results of the technology demonstrations to academic and military interests. Furthermore, AFRL will infuse the results of the technologies into military and industrial applications that can primarily aid the warfighter.

The operations team consists of the following positions.

Mission Controller (MC). This individual is responsible for real-time contact execution, interface with the Air Force Satellite Control Network (AFSCN) for ground system setup, checkout, and post-pass reconfiguration of AFSCN resources. Also, the MC is responsible for determination and execution of all Level I anomalies and proper notification of program office and contractor personnel.

Orbit Analyst (OA). The OA is responsible for orbit-related file generation in support of ground operations. Products provided by the OA include standard orbit events tables, ground acquisition tables, pointing angles, and the vehicle state vector. The OA also provides tracking data to the FTHSI program office for image collection activities.

Satellite Engineer (SE). The SE is responsible for operations planning activities. The SE supports LEO real-time command execution, vehicle anomaly investigation, and anomaly plan execution. Daily activities consist of AFSCN resource deconfliction, pass plan and 24-hour board generation, experiment command file retrieval, real-time command and SPC block builds, and command procedure builds. Weekly activities performed by the SE include development of a Program Action Plan (PAP) to request AFSCN resources.

Satellite Operations Engineer (SOE). The SOE is in command of the RSC during mission operations and ensures that resources are available to properly command the MightySat vehicle. She is responsible for the conduct of the operations center and ensures that operations performed by the SE, MC, and OA are timely and applicable for the activities at hand.

MSPO Technical Advisor (MSPO TA). This individual is responsible for providing timely technical inputs and recommendations regarding spacecraft systems. The MSPO TA provides equipment, personnel, operations documentation and technical documentation as required during mission operations. The MSPO TA provides interface between the experimenters and Spectrum Astro and the Mission Director's Representative (MDR) and SOE.

Spectrum Astro. Spectrum Astro provides pertinent technical assistance to the MSPO TA during LEO activities. This information enables the team to make informed and accurate decisions to ensure the safety and optimum performance of the MightySat vehicle. After LEO activities, Spectrum Astro will continue to provide assistance with trending data, working spacecraft anomalies, and maintenance of the space vehicle.

Experimenters. The experimenters will perform payload initialization activities on the MightySat vehicle during LEO. Once the payload initialization operations are completed, the experimenters will then perform routine operations with their payloads. Finally, the experimenters will provide inputs during anomalous activities.

Mission Director (MD). The MD is responsible for the MightySat II mission from launch to the end of life. He directs all mission activities, including launch and operations. This individual comes from the SMC/TEL organization (Space Test Program director).

Mission Director's Representative (MDR). This individual is the day-to-day representative of the MD. It is this person's duty to ensure that the MD's interests are represented. The MDR is in charge of the mission control team (MCT), which consists of all the positions listed above. The MDR is the interface between the program office and operations community. The MDR is instrumental in the conduct of LEO and anomaly operations.

Preparing for Mission Operations

Several undertakings helped prepare the MightySat mission and its team for on-orbit operations. First of all, the RSC needed to be able to communicate with the space vehicle through the AFSCN. Furthermore, this capability had to be verified before rehearsal and launch. Second, data coming from the spacecraft while on orbit needed to be processed and distributed to their respective organizations, whether payload or bus data. Finally, the team described in the last section needs to be proficient in operating the spacecraft to ensure safe and efficient operations. The following subsections describe this process in detail.

RSC/MightySat II Communication Preparations

For the RSC to communicate with the MightySat vehicle on-orbit, several software tools were developed to enable this capability. These tools included the AutoPlan Tool, the Queue Management Tool, the Command Builder, and the Tasking Parser. These software tools worked in conjunction with the telemetry and command databases developed by Spectrum Astro for development of the MightySat spacecraft. Also, the command builder development was aided by prior development of spacecraft functional tests by Spectrum Astro. These test scripts were written in the PERL language and were easily converted into the command builder text. This was especially beneficial due to the short development time required by the RSC when MightySat mission development was occurring. The FTHSI program office is the primary user of the command builder tool; personnel input orbital parameters and target information, and the tool returns the correct sequence of spacecraft commands to effect such maneuvering.

Once the MightySat tools were developed, mission compatibility tests were performed to verify the compatibility of MightySat with the RSC and the AFSCN. Three distinct mission compatibility tests were conducted. The first was the radio frequency (RF) compatibility test. This test verified the ability of MightySat's transponder to receive encrypted commands and send encrypted telemetry via RF to a deployable test van that was moved to the AEF. The purpose of the test van was to emulate an AFSCN ground station and had nearly identical equipment. This test was a resounding success—encrypted commands were sent and encrypted telemetry was received. The problem that surfaced was described in the I&T portion of this paper, regarding repairs to the NSX.

The next mission compatibility test ran the remaining functional tests for the MightySat vehicle to verify compatibility with the RSC. The T-1 data line between the AEF and RSC was utilized for this portion of the testing. All remaining diagnostic tests were performed, including EPS, ACS, SMATTE, and FTHSI testing. All of these tests completed with no major problems. After the mission compatibility test, changes were made then verified in the database, RSC system, and MightySat vehicle.

The final compatibility test was the Launch-Base Mission Compatibility Test (LBMCT). The purpose of the LBMCT was to demonstrate commanding ability and compatibility between the space vehicle and the RSC through the AFSCN. The vehicle, this time located at Vandenberg AFB, transceived via horn antenna to COOK ground station. COOK relayed data and commands between Vandenberg and either Schriever AFB or Onizuka AS, which then sent the data through dedicated hard-line to the RSC. As with the other tests, the LBCT was a resounding success. During this time, an FTHSI image collect was performed and data transferred back to the RSC.

The mission compatibility tests successes have instilled high confidence that MightySat operations will happen as expected on-orbit. Furthermore, commanding through the AFSCN should be entirely uneventful due to thorough testing.

Developing a Data Processing Capability

Once the data is downloaded, it is decrypted, processed and reformatted to be compatible with the experimenters' requirements. This data manipulation is provided through the RSC data processing system. Then the data is placed on the RSC's Automated Data Distribution Server (ADDS) for the payloaders to download and process. Access to ADDS is encrypted and requires a decryption card and software to connect to it. All data products are now accessible to all the experimenters. Also, the ability to send planning files to the RSC is enabled through remote use of the same system.

MightySat Team Preparation for Mission Ops

Several steps were taken to ensure that the mission operations team was fully prepared for on-orbit operations. Throughout the satellite and mission planning phases, the RSC operations personnel were heavily involved through working groups, rehearsal committee meetings, and other activities. Formal training began in earnest with a training session provided by Spectrum Astro; this training was highly beneficial to convey data and satellite knowledge to the entire MCT.

Another method of preparing the team for mission operations was through exercises. The purpose of the exercises was for the core operations team (SMC/TEO) to practice operations and to demonstrate performance of the tools required to perform the MightySat mission. Three exercises were performed. The first exercise demonstrated ability for the RSC to perform a contact and provide basic training for the team; the second exercise provided for planning, queue management, ground cryptographic unit (KI-17) processing, command building, and data processing. The final exercise tested long-term planning, 24-hour nominal planning, and the MCT use of systems, tools, and procedures. The final exercise also placed heavy emphasis on FTHSI processing. The results of the exercises revealed that additional work was needed to ensure that the core team was fully prepared. Consequently, the operations team ensured that all holes in the operations process were filled. This resulted in a smooth-running operation that has helped the entire team perform well during rehearsals.

Rehearsals provided the whole team the opportunity to see how operations will occur and how to respond to various anomalous situations. Five rehearsals were performed: 1) the first 72 hours of LEO; 2) the first 32 hours of LEO, FTHSI initialization and an image collection; 3) LEO, FTHSI image collections and ACS testing; 4) SMATTE initialization and checkout, and SMATTE and FTHSI operations; and 5) dress rehearsal—the first 36 hours of LEO operations.

Shortcomings in the RSC operations flow, as well as space vehicle issues, were revealed and resolved. For example, the operations flow, which originated with performing near-term and daily taskings, transitioned to performing tasks for vehicle checkout as time permitted and as resources were available. The result was a more relaxed operations tempo, instead of cramming too many objectives into too few contacts. Another example of the benefits of rehearsals was to focus more on ACS activities. These activities were more complex than originally anticipated. More attention was paid to this critical activity, as FTHSI success depends to a large degree on the accuracy of the ACS. Another benefit was the focus on contingency procedures in the event of anomalies. Rehearsals revealed a deficiency in scripted contingencies in response to anomalies. This prompted the MSPO to revise and create all possible anomalies. As a result of rehearsals, exercises, and contingency refinement, the team was well prepared for launch and early orbit checkout.

As mentioned earlier, much of the testing and rehearsing occurred on the MightySat Integrated Testbed (MIT) and through utilizing the T-1 link to the RSC. The MIT was instrumental in simulating spacecraft activities during rehearsals and proved essential in validating changes to database parameters, prior to testing them on the space vehicle. Also via the MIT, operators were able to insert spacecraft anomalies, which were then identified and resolved by the operations team. In addition to their I&T support, J&T personnel greatly assisted the operations team, and they will continue to provide valuable experience to the operations team and aid in on-orbit operations. The MIT and AC1000 simulator are further discussed in the next section.

Some Lessons Learned

Command and Telemetry Playback

AstroRT commanding and telemetry software for MightySat II has no capability to parse data to Excel, MatLab, or other data processing systems in real-time, while conducting either spacecraft or MIT operations. The spacecraft ground-based operating system, known as AstroRT, was only capable of doing real-time "playback" of command and telemetry files recorded as "as run" files. This resulted in having to search for key information in the playback mode with no ability to pause or manipulate the data for trending, failure or problem anomaly resolution, or system improvements. Although AstroRT did have the ability to construct plots or graphs in real time, these were again not available outboard of the ground system. The result of not having this capability to separately parse the command and telemetry data was that historical data (trending) and statistical correlation of data was nearly impossible to do. This increased risk to the spacecraft through not having readily accessible data on spacecraft parameters important for anomaly resolution in spacecraft I&T. The team's concern over this lack of data parsing resulted in the development of a separate data storage, trending and analysis tool during the final stages of MightySat's I&T phase. This tool, based largely on AstroRT, allows real-time data parsing, analysis, storage and trending from data taken both from the satellite directly during I&T or from on-orbit download. This tool—MightySat Operational Trending & Analysis System (MOTAS)—came to fruition after completion of space vehicle I&T. Therefore, the 1500 hours of spacecraft "run time" during this period were not recorded and trended for examination of long-term operating effects or anomalous behavior. The MOTAS has proven to be extremely useful in the real-time evaluation of spacecraft performance, which assisted in anomaly resolution, during mission operations rehearsals with the MIT and has demonstrated the capability to provide summary files of key spacecraft attributes for use by spacecraft engineers and program managers. The time savings as a result of automated data gathering and analysis routines within MOTAS allows satellite engineers to concentrate more closely on real-time data observation rather than laborious post-processing efforts.

MightySat Integrated Testbed (MIT) and AC1000 Simulator

As discussed earlier, the spacecraft bus contractor's method of spacecraft development incorporated two advantageous components called the MIT and the AC1000 simulator. MightySat II is fundamentally a bus built around the size 6U VME electronic card standard. The MIT became a "virtual" spacecraft by which card development, software, power, command and data handling and payload drivers could be developed, tested, modified and improved without risk to the flight spacecraft. Combined with another software/computer system known as the AC1000, Spectrum Astro successfully simulated all ACS inputs and outputs and combined them with the MIT to conduct ACS algorithm development and troubleshooting. The combined MIT/AC1000 became critical to final I&T of the spacecraft, as well as to provide real-time capability to rehearse space vehicle operations and ground system compatibility.

Spacecraft Deployment Sequence – Solar Array Deployment Timing

The spacecraft deployment sequence was designed to hold the solar arrays in the stowed configuration after nulling tip-off rates (post launch vehicle separation) in the event of separation in eclipse. This design consideration included the view that array deployment power and the additional power required for slew of the spacecraft after array deployment would be better preserved until the first sunlight opportunity. The result of this design decision is that, at best, only one quarter (one of four solar array panels) of the power generation available in sunlight is available should the battery depth of discharge (DOD) not allow deployment of the SARMs. Although this design might suggest prudent preservation of power margins for the satellite, another view is that far less risk is taken with a design that deploys the solar arrays immediately. Based on historical evidence showing deployable mechanisms as a leading cause of spacecraft failures, analyses should be conducted to discern which method of design results in the least cumulative risk to the spacecraft. The preferred deployment of the solar arrays as soon as possible (in eclipse or sunlight) would, in MightySat's case, maximize the likelihood of solar illumination in the event of spacecraft tumble or unknown configuration.

Live Bus/Dead Bus: Power Management

An important, and potentially dangerous lesson learned in design and build of the satellite stems from the programmatic development of MightySat II to be launch capable for both Space Transport System (Shuttle) and OSP. The notion of developing a flexible bus, capable of launching from both the Shuttle and a dedicated, single-use launch vehicle was driven by both funding availability and programmatic necessity. It also meant, however, that certain attributes of design could not be finalized until final selection of that launch vehicle.

The spacecraft contractor chose to pursue more rigorously the likelihood of a Shuttle launch utilizing the newly developed Shuttle Hitchhiker Experiment Launcher System (SHELS). Use of the SHELS, and flight on the Shuttle, required MightySat to be developed as a "dead bus" by which a series of actuation switches would initialize the spacecraft's turn-on sequence. During the development process and after funding was made available for flight of MightySat II on Minotaur 2, a quick redirection of design was implemented to the spacecraft bus. New design changes would now include flight of an actively powered spacecraft through countdown and launch via an electrical power umbilical available with Minotaur 2. This "fly-away" umbilical would obviate the need for the multiply redundant separation switches and ensure battery top-off until the time of launch. Unfortunately, development cost of this umbilical proved prohibitive. As a result, MightySat II, which was already designed to launch with a partially activated bus (command interface unit, essential bus backplane, and receiver), would have to launch while powered by internal spacecraft battery, with no capability for top-off prior to some defined period before launch.

With MightySat's launch on battery power, the batteries are 40 percent discharged at the first opportunity for ground contact. Such a high DOD already places the spacecraft in an under-voltage trip condition where payload power bus and payloads shed in nominal operations. Although this condition is obviously not of concern for initialization and early checkout of the spacecraft, it points to the less than desirable result of this chain of events leading up to the satellite's required launch conditions.

Figure 21. Minotaur 1 launch (Jan 00) – MightySat II launched on Minotaur 2.

Automated Test Scripts & Configuration Control

Automated test scripts were written in PERL language for development and I&T of the spacecraft bus prior to delivery to AFRL and were used quite effectively. These scripts naturally became the "standard" routines by which later functional testing of the fully integrated space vehicle would be conducted at the AEF. A key lesson learned by the MightySat II team was the need for ensuring that such automated scripts kept pace with the actual hardware configuration of the spacecraft. It was a potent reminder of the need for configuration control discipline.

A PERL script written for test of the spacecraft's power distribution unit (PDU) was completed prior to delivery of the spacecraft bus to AFRL. This script simply cycled each of the spacecraft's power relays, including those held for use by payloads yet to be integrated to the bus. Relays designed into the bus included those for use of a payload, which was later demanifested due to lack of technical maturity. Many months later, PicoSats was manifested as a payload of opportunity, and command and telemetry mnemonics assigned for the earlier payload had to be used for PicoSats. The PicoSats experiment was delivered to AFRL and successfully integrated to the spacecraft. Later in the test flow, a complete functional test was conducted, incorporating in part the earlier developed PDU relay script in PERL. Without the benefit of having command and telemetry mnemonics that represented actual PicoSats experiment functions, the PDU relay script did not take into account the installation of flight hardware on the spacecraft. Unfortunately, when the relays were exercised by the script, the commands to fire the PicoSats actuator were sent to spacecraft, and the fully integrated flight model PicoSats were immediately ejected from the satellite onto the satellite support stand. The resulting damage from the accident required refurbishment of the PicoSats, as well as re-integration of the non-explosive actuator that ejects them from MightySat II

Although the automated PERL scripts were a tremendous boon to space vehicle I&T at large, the team learned that spacecraft developers need to use a system by which such scripts must mirror the actual flight hardware configuration. This may largely be controlled by placing the test scripts in system configuration control, such that when hardware changes are made, scripts are reviewed, edited, and approved prior to use. This experience also suggests that updating the command and telemetry database must likewise contain mnemonics that directly tie to the payload or spacecraft functions being commanded.

Common Bus for Plug ‘n Play Experiments

One of MightySat’s principle objectives is to demonstrate the ability of a common bus design to accommodate a wide range of varying space-flight experiments. MightySat II has been successful in accomplishing this objective. However, through preliminary mission definition and experiments acquisition for the second MightySat II mission (II.2), AFRL learned that the bus required significant redesign and adaptation for different experiments. From this experience, it became apparent that assembly-line production of buses for experiment-bearing satellites is not necessarily the answer to meeting space-flight objectives.

Single-String Experimental Transponder

Over the course of executing the MightySat II program, there were numerous other lessons learned, but the last one to be noted in this paper involves the use of the experimental transponder (NSX) as the sole communication link for the space vehicle. While NSX technology is not exactly cutting edge, its miniaturization forges new territory. Early in the program, the team decided that NSX would be technically sound and that cost for a backup transponder would be excessive. Experience proved otherwise—while the NSX repeatedly demonstrated successful operation during ground testing, it remains a high technical risk to successful satellite-to-ground communication.

Summary

In summary, this paper has explained the architecture of the MightySat II space vehicle, including its components, subsystems, and experimental payloads. MightySat II is an extremely robust space vehicle, highly capable of demonstrating its on-board emerging AFRL technologies for tomorrow’s warfighter. This paper also detailed MightySat’s integration and testing efforts, mission operations, and included some lessons learned for a small satellite program.