SSC99-I-3

MIGHTYSAT I: IN SPACE

Capt Barbara Braun
USAF Research Laboratory
3550 Aberdeen Ave SE, Kirtland AFB, NM
(505) 846-0652
barbara.braun@comanche.plk.af.mil

Robert Davis
The Aerospace Corporation
3550 Aberdeen Ave SE, Kirtland AFB, NM
(505) 846-0807
robert.j.davis@plk.af.mil

Thomas Itchkawich
Orbital Sciences Corporation
1531 Westbranch Drive, McLean, VA
(703) 883-2684
itchkawich.tom@orbital.com

Todd Goforth
Maxwell Laboratories
3550 Aberdeen Ave SE, Kirtland AFB, NM
(505) 846-6516
gofortht@plk.af.mil

Abstract. MightySat is a United States Air Force (USAF) Research Laboratory multi-mission, small satellite program dedicated to providing frequent, inexpensive, on-orbit demonstrations of high-payoff space system technologies. MightySat I, the 140lb pathfinder satellite of the MightySat series, was ejected from the Space Shuttle Endeavor on the 15th of December, 1998. Contact with the satellite was established one hour after ejection, and MightySat I has been performing robustly on-orbit ever since. This paper provides an overview of the MightySat I satellite and its experiments: a lightweight composite structure, high-efficiency solar panels, low-power microelectronics, low-shock release devices, and micro-particle impact detectors. The design, integration, and test process is described, as is the process of Space Shuttle integration and final testing. The paper then discusses the on-orbit operations, coordinated from the Space and Missile Systems Center's Test and Evaluation directorate (SMC/TE) at Kirtland AFB, NM, and conducted using two UHF ground stations in Virginia and New Mexico. The launch, initial contact, and early-orbit checkout sequence of events is described. The paper describes payload initialization and on-orbit data collection, and highlights some of the payload data currently being collected. A brief discussion of the upcoming MightySat II satellites and missions is also included.

MIGHTYSAT PROGRAM

The introduction of advanced, often enabling, space system technologies into USAF operational satellites has traditionally been a challenging problem. The term "operational systems" refers to the critical surveillance, communications, navigation, and other missions performed by the fleet of satellites in the US Department of Defense space architecture. These systems are generally complex and expensive, often requiring a decade to develop and hundreds of millions of dollars to build and launch. Accepting the risk associated with introducing advanced technology components into programs of this magnitude is very difficult for USAF program directors. Even when such technologies are key to the success of the mission, the introduction of unproven technology into new operational space programs or block-changes to existing systems has traditionally been a source of significant program cost growth and development delays. More importantly, on-orbit failure or unexpected degradation of advanced technology components in critical defense systems is simply not acceptable for the successful execution of the Air Force's space mission.

The primary objective of the MightySat program is to reduce the risk of transitioning advanced space system technologies from the laboratory to operational USAF space applications by providing on-orbit demonstration of emerging technologies. The US Air Force Research Laboratory (AFRL) Space Vehicles Directorate, based in Albuquerque, New Mexico, is the USAF center for space systems research and development, with the charter to explore, develop and transition enabling technologies to the operational users. The Space Vehicles Directorate has advanced technology development programs underway in nearly all elements of space systems. These programs are in various stages of maturity, from fundamental scientific research to conceptual design to actual hardware fabrication and testing. Promising technologies that emerge from this process are candidates for demonstration on a MightySat mission. Data from the MightySat missions will then be used to support decisions on the readiness of the specific technology for application in USAF missions. The difficult technology insertion decision can then be made with increased confidence and with considerably reduced risk.

In order to effectively make emerging technologies available to operational systems, the technologies must be demonstrated in a timely manner. Thus MightySat seeks to shorten the timeline for technology demonstration to something on the order of 2-3 years from payload conception to launch. Demonstrating emerging technologies is also risky, and fiscal constraints dictate that MightySat technology demonstration missions be significantly less expensive than historical military experimental satellite programs. The total cost goal of each MightySat mission, including contracted spacecraft development, government program execution expenses, payload integration, system testing, launch, and mission operations is $10M. For MightySat I, a simple pathfinder mission for the long-term MightySat program, the total mission cost (including all of the above) will be near $7M.

Although technology demonstration and transition is the primary mission objective for the MightySat program, the Air Force also realizes several collateral benefits from this effort. An intangible but very important benefit of the MightySat effort is the invaluable experience gained by lab personnel who support the many aspects of the MightySat program. MightySat is a microcosm of the larger, more complex space programs in which many of the Research Laboratory's Air Force officers will eventually hold positions of significant responsibility. MightySat offers real-world lessons in systems engineering, payload integration, environmental test, launch operations, and on-orbit satellite command & control.

The MightySat I program is managed by AFRL's Space Vehicles Directorate in Albuquerque, NM. The contractor for the MightySat I spacecraft bus (a refurbishment of the existing "XSAT" bus, intitiated under a NASA contract in 1988-90) is Orbital Sciences Corporation (OSC) in McLean, VA (formerly CTA Space Systems). MightySat II is a series of up to five small satellite missions occurring over the next decade, with the spacecraft bus being developed by Spectrum Astro, Inc. of Gilbert, AZ. The USAF Space & Missile Systems Center's Test and Evaluation Directorate, also based in Albuquerque, leads mission operations and launch coordination. Since the Space Shuttle is the primary launch vehicle for the MightySat program, NASA is also a key member of the MightySat team.

The MightySat effort has two distinct groups of customers for whom the advanced demonstrations are conducted: technology users and technology developers. The ultimate customers for the MightySat program are the developers and users of USAF operational space systems at the USAF Space & Missile Systems Center (Los Angeles, CA), US Space Command and Air Force Space Command (Colorado Springs, CO). These organizations make the decisions about insertion of advanced space systems technologies into operational applications. The second, more immediate customers for the MightySat program are the technology developers within AFRL who propose experiments or technology demonstrations.

MIGHTYSAT I SPACECRAFT

The drawing of Figure 1 shows the overall dimensions of the MightySat I vehicle. The vehicle size was dictated by the static and dynamic envelope constraints of the Shuttle Hitchhiker canister, and the vehicle weight was limited by the capability of the ejector. In order to avoid deployable antennae (which NASA discourages for safety reasons), four fixed UHF antenna blades are hard-mounted to the top of the vehicle. This configuration results in the MightySat I vehicle protruding above the Hitchhiker canister, which is flown without the traditional motorized lid for this flight.

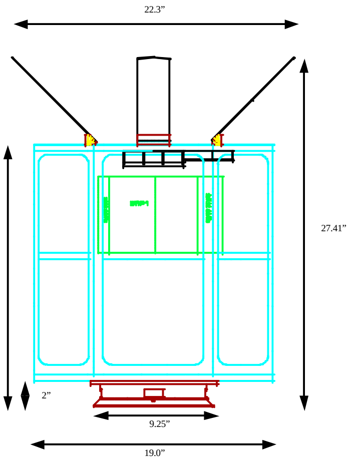


Figure 1: MightySat I Dimensions

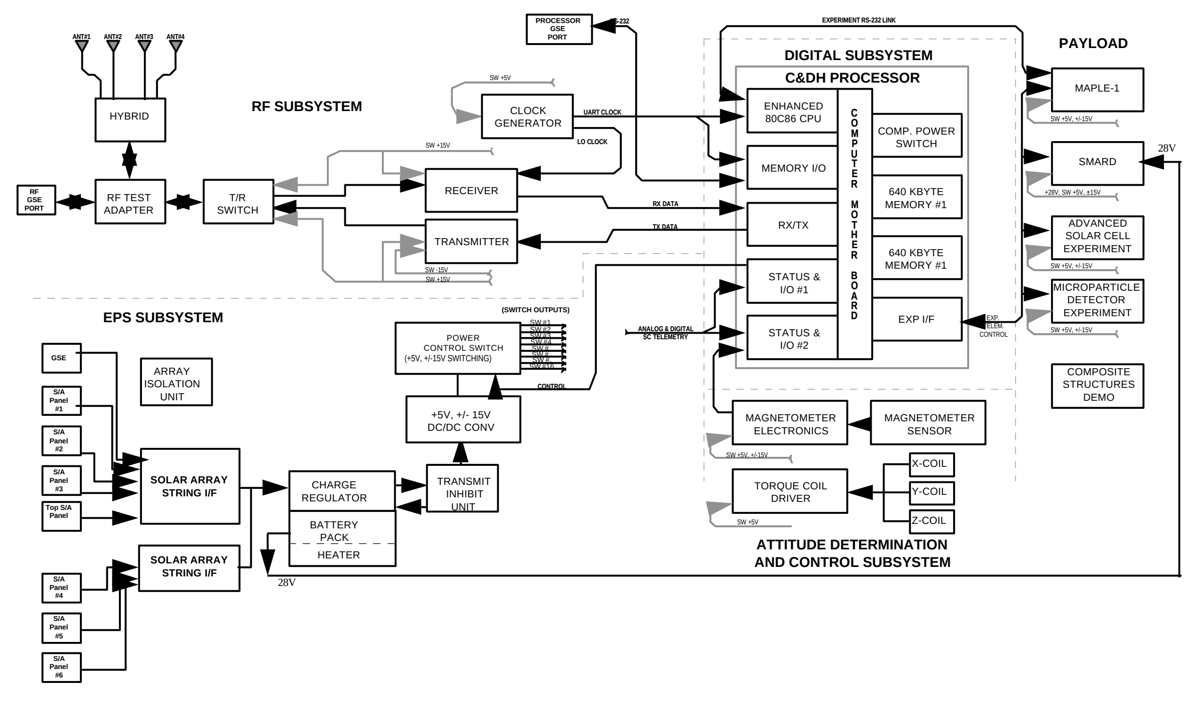


Figure 2: System Block Diagram

The MightySat I structure is characterized by three decks supported by six structural frames, which make up a hexagonal prism body. The bottom deck houses spacecraft components, such as the card cage, power, communications, and attitude control system hardware. The middle deck is used primarily for two of the payloads. The upper deck supports a solar panel, some experimental thermal control hardware (calorimeters & thermostats) sponsored by the spacecraft contractor, and four paddle antennae. The center of mass for the MightySat I vehicle is well within the NASA requirements of no more than 10.25” from the separation plane in the Z direction, and no more than 0.25” from the geometric center in the X and Y directions.

Table 1 provides a top-level overview of key performance parameters for the MightySat I spacecraft. Although the MightySat I spacecraft does not have a large degree of flexibility or redundancy, the system is a very capable space platform for meeting the requirements of this specific mission, especially in light of the cost and development schedule.

Figure 2 is the overall system block diagram for the MightySat I vehicle. Functionally, the spacecraft has four major elements: Command & Data Handling (C&DH) Subsystem, Electrical Power Subsystem (EPS), Communications Subsystem (RF), and the Attitude Determination and Control Subsystem (ADACS). In addition, there are mission unique components that were developed for collecting solar cell performance data, and for addressing NASA safety concerns.

Table 1: MightySat I Key Parameters

Total Space Vehicle Weight	140 lbs
Payload Weight	37 lbs
Power Generation	0 - 32W
Orbit Average Power	14-27W
Spacecraft Orbit Avg Power Usage	12W
Uplink Rate/Downlink Rate	2400/9600 bps
Attitude Knowledge	+/- 5 deg

Command & Data Handling Subsystem

At the heart of the MightySat I system is the C&DH, which controls all spacecraft functionality. Nine electronic boards make up the C&DH subsystem, which performs the following functions: 1) accepts and executes ground commands, 2) controls all power switching and commanding of the payload and spacecraft elements, 3) collects and stores spacecraft and payload telemetry, 4) schedules and controls communications with the ground, 5) performs all spacecraft housekeeping and spacecraft state-of-health functions.

Flight Software

The MightySat Flight Software has heritage from many other CTASS satellites, including the Air Force STEP and REX series. Processor software is written in Assembly language and "C", and operates under Ready Systems' Virtual Run Time Executive (VRTX) operating system. Like the C&DH hardware, the MightySat I software architecture is relatively simple. Following a Start-up Routine, software control is passed to the VRTX operating system, which runs the MAIN task. MAIN, which is the highest priority task after satellite initialization, maintains the schedule, initiates execution of routines based upon ground commands, and passes control to the various sub-tasks as required.

Electrical Power Subsystem

The MightySat EPS consists of seven solar panels, a single 21-cell NiCd battery, a charge regulator, a DC/DC Converter, and a Power Control Switch. Although most of the EPS design has flight heritage, the Solar Array String Interface (SASI) was modified significantly to permit precise measurement of solar panel performance as part of the ASCE payload. Power from the solar panels is routed through the Solar Array String Interfaces (SASI's) to the battery charge regulator. The battery charge regulator is connected to the bus loads through an isolation diode, and permits the battery to supply power when the need exceeds the power generated by the solar panels. The MightySat I battery is a single 4 Amp-hr unit made of 21 Sanyo NiCd "D" cells wired in series. From the battery, power flows through a DC/DC converter to the Power Control Switch, a bank of 16 transistors that switch power to all bus and payload components based upon commanding from the C&DH.

Attitude Determination and Control Subsystem

The Attitude Determination and Control Subsystem (ADACS) configuration consists of a three-axis magnetometer and two coarse sun sensors for attitude determination, plus three torque coils and associated driver electronics for attitude control. In order to optimize power generation and maintain a simple, low-cost approach, the vehicle spins at 3 rpm about the vehicle "Y" axis, with the spin axis oriented normal to the orbit plane. This attitude is best illustrated in the orbit visualization depiction of Figure 5. Though the "Y" axis would appear to be an unconventional choice, it is the maximum moment of inertia axis and is acceptable from a power generation perspective.

RF Communications Subsystem

The MightySat I communications architecture consists of a simple, half-duplex (306.775 MHz) approach with a 2400 bps FSK uplink and 9600 bps BPSK downlink. The spacecraft RF Subsystem consists of a receiver, transmitter, transmit/receive switch, antenna hybrid, four blade antennae, RF test adapter and clock generator. The BPSK modulated transmitter has an output power of 14W with an efficiency of 60%. The receiver is a fixed frequency, single conversion unit with a 2.5 dB noise figure and a 10 dB S/N ratio at an input signal level of -120 dBm. Four quarter-wave monopole antennae are mounted 90 degrees apart on the top deck of the MightySat vehicle to produce a quasi-omnidirectional pattern. The MightySat RF communications link has about a 20 dB margin for both uplink and downlink at a 5 degree elevation angle.

Payloads

MightySat I has five advanced technology demonstration experiments. Two of the demonstrations are considered Experimental Bus Components, because they provide essential bus functionality to MightySat I, in addition to acting as advanced technology demonstrations. These are the Advanced Composite Structure and the Advanced Solar Cell Experiment (ASCE). The remaining three experiments are considered Stand Alone Experiments. These include the Microsystem And Packaging experiment for Low-Power Electronics (MAPLE-1), the Shape Memory Actuated Release Devices (SMARD) experiment, and the Microparticle Impact Detector (MPID) experiment. Details on each of these experiments can be found in the section on on-orbit results.

LAUNCH APPROACH

The primary launch approach for the MightySat program is ejection from the Space Shuttle. The MightySat I vehicle was designed and built for direct compatibility with the standard STS Hitchhiker Ejection System (HES). The chief reason for this approach is cost; as a USAF payload, the cost of launching from the Space Shuttle is consistent with the cost goals of the program. Launch system reliability, and a relatively high frequency of launch opportunities as a secondary payload are other attractive features of the Shuttle. However, Space Shuttle launch does have some rather significant drawbacks, such as the program impact and manpower costs of navigating through the extensive NASA Safety Review Process. Also, the Shuttle orbits are not always optimal for technology demonstrations that require special orbits, such as sun synchronous or high-radiation. Satellites without on-board propulsion also face short lifetimes, due to the low Shuttle orbit. For this reason, the MightySat II series is being designed with alternate launch systems in mind, to take advantage of any potential low-cost launch opportunity that may arise.

MightySat I has a standard Marman Ring interface with the HES. Figure 3 shows the MightySat I vehicle in the Hitchhiker canister with the standard motorized lid removed. The interface with the HES is strictly mechanical; no power, telemetry, or command interface exists between the Shuttle and the MightySat I vehicle. MightySat is essentially "inert" while in the canister; all spacecraft components are isolated from power sources. The canister is equipped with survival heaters that will keep the satellite temperature above 0°C in the cargo bay; aside from these survival heaters, no other active thermal control exists in the Hitchhiker canister. Safety issues associated with launching on a manned system have impacted the MightySat I program from many aspects. The design of two MightySat I components were particularly driven by safety-related concerns: the Transmit Inhibit Unit and the Nickel-Cadmium battery. The Transmit Inhibit Unit (TIU) is an electronic component that was added to the MightySat I design specifically to address the safety concerns of launching on the Shuttle. This unit essentially contains a series of electrical inhibits that block power from reaching "hazardous" components, such as the spacecraft transmitter. NASA requirements prohibit MightySat transmitter activity within 30 feet of the Shuttle. Other hazards associated with electronic board shorting were most easily addressed by simply ensuring that the MightySat system was powered OFF while in the canister.

Another serious concern of the NASA Safety Review Panel was the MightySat battery. MightySat uses commercial Sanyo Nickel Cadmium "D" cells, which do not have the typical design and test documentation associated with hardware developed for aerospace applications. Although these cells have flown for a decade on many OSC small satellites without a single cell failure on orbit, the MightySat team faced several design and testing challenges to meet NASA requirements. In order to better understand the nature of the NiCd cells, the MightySat program sponsored a series of tests at The Aerospace Corporation to experimentally determine the maximum operating pressure of the cells in off-nominal conditions, such as overcharge and reversal. The pressure at which the cells would vent was also determined experimentally.

Figure 3: MightySat I in Hitchhiker Can

In addition to testing the cells, the MightySat team was tasked with designing a battery "box" which would absorb and contain the potentially hazardous potassium hydroxide (KOH) electrolyte in the event of cell venting. The design solution was an aluminum box with special cut-out regions adjacent to cell vents that is filled with an absorbent material. These regions contain any leaked electrolyte in the absorbent material, while not permitting shorting across paths of leaked electrolyte. A microporous Teflon filter is also used over a vent hole in the battery box, so that hazardous gases will escape from the battery box. In this case, an originally low-cost battery approach became significantly more expensive due to the manpower and testing required to meet the requirements of the NASA safety process. The MightySat I battery experience is a valuable "lesson learned" for the long term MightySat program.

MISSION OPERATIONS CONCEPT

Three stand-alone, UHF Ground Control Stations (GCS) were developed for the MightySat program. Two were designed for satellite mission operations, and the third was dedicated to ground testing. The system shown, which connects to a steerable 10 ft diameter dish antenna, was installed at Kirtland Air Force Base (Albuquerque, NM) and at OSC (Dulles, VA) to provide two locations for satellite contact. The GCS was designed and built by Deskin Research Group (DRG), Inc of Santa Clara, CA using a large amount of existing hardware from previous government programs. This allowed the ground control stations to be acquired at low cost, but also produced some ground station problems. Because the components of the ground stations were acquired from several different programs, the antenna's positioner was undersized for the weight of the antenna and hood assembly. This led to problems with maneuvering the antenna through elevations near 90°. The wear and tear on the positioners was also extensive, requiring rework and the addition of counterweights to prevent positioner breakdowns.

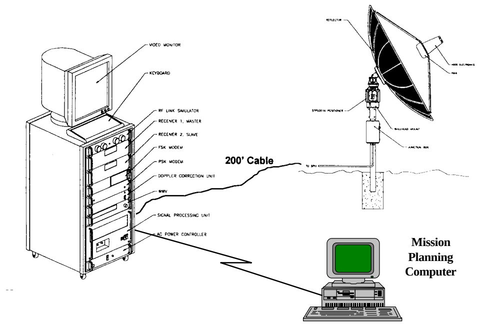


Figure 4: Ground System Architecture

MightySat I's ground control architecture is based upon the use of two PCs, as shown in Figure 4. The Mission Planning Computer (MPC) is the primary operator interface. Commands are selected from a database stored on the MPC for uplink to the satellite, and downlinked telemetry is displayed on the MPC for operator viewing and post-processing. Also, the MPC contains orbit visualization and propagation software for use in scheduling satellite contacts and other mission planning needs. The second PC, in the Signal Processing Unit, controls the GCS RF hardware and orchestrates the communications session between the ground and the satellite. This PC interfaces directly with the MPC to generate a track file for steering the dish antenna during contact with the satellite. In addition to the transmitter, dual receivers, and modems, the GCS contains a timing source (WWV or GPS) and Doppler correction hardware. Other PCs in the operations area are used to process telemetry, develop long-range planning boards, and place data on a public FTP site for retrieval by payloaders.

The Concept of Operations for the MightySat I vehicle is based largely upon experience from similar small satellite programs, most notably RADCAL. MightySat vehicles are operated by personnel from the Space & Missile Systems Center's Test and Evaluation Directorate (SMC/TE), an organization with a long history of performing mission operations for non-operational Air Force space systems. The main center for MightySat I operations is at KAFB. Contacts at the Dulles ground site are managed through remote link from KAFB, using modems, phone lines, and special remote software.

After preparation by the operations team, the actual MightySat I communications session occurs autonomously. Several minutes before a contact, the ground system prepositions the antenna at the start of the satellite's track. At the satellite's "rise time," the ground system begins executing its track file, positioning the antenna to follow the satellite's track through space. The satellite initiates all communications events, based upon a time-tagged communications event in its Scheduler. In a typical pass, the satellite begins by downloading payload data to the GCS, which stores the data for post-pass processing. Towards the middle of the pass, the satellite and ground station conduct bi-directional communications, in which commands are uplinked to the satellite Scheduler and MightySat I state-of-health data is downlinked. After this exchange, the satellite resumes downlink of payload data.

The Aerospace Corporation developed a MightySat I mission simulation model for visualization of the orbit and to gain a better understanding of power and communications issues. Figure 5 shows an image from this simulation tool, with the MightySat I vehicle in its expected orbit and attitude. The spin axis for the vehicle is oriented directly out of the orbital plane, which causes the antennae to alternately point towards then away from the earth. MightySat I has between six and nine passes each day, divided fairly evenly between the KAFB and the Dulles ground sites. Each pass can be from one to six minutes long. The passes occur about 90 minutes apart, followed by a long period (up to 14 hrs) of no contact with the vehicle.

INTEGRATION AND TEST

During spacecraft development at OSC, each of the spacecraft components was subjected to thermal cycling and random vibration acceptance testing to ensure quality of the workmanship. In some cases, the component was of a new design (e.g. TIU), and the testing served as a qualification as well as acceptance test. Once assembled, the spacecraft (without payloads) underwent EMI/EMC testing and thermal cycle testing with electronic check-outs of the full functionality of the spacecraft at hot and cold dwells.

In parallel, each of the MightySat payloads underwent its own thermal cycle and vibration testing. A second composite structure, identical to the flight unit, was fabricated and tested in order to gain an early understanding of the structural dynamics of the vehicle. With mass mock-ups in place for the internal components, the "engineering structure" was put through random vibration testing, sine burst testing for structural qualification, and sine sweep testing to measure the spacecraft's natural frequency. As a result of this testing, modifications were made to the flight structure to make it more robust. The use of an engineering structure saved countless hours of rework to the flight structure, and reduced the risk of damaging critical flight components.

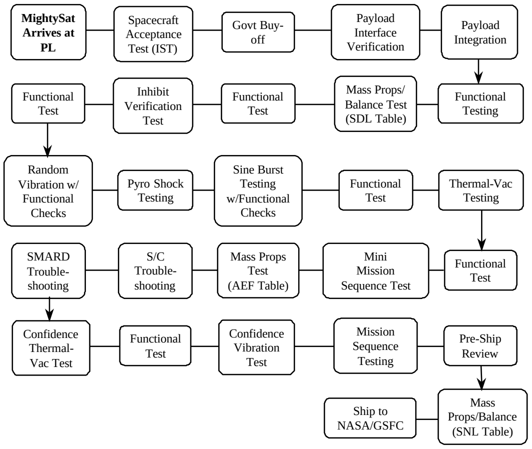


Figure 5: KAFB Integration and Test Flow

Payload Integration

Figure 6 outlines the flight model integration and test effort at KAFB. Upon delivery of the spacecraft to the USAF in November of 1996, the government took the lead in integrating and checking the MAPLE-1, SMARD, ASCE, and MPID payloads. Payload integration took nearly two months. During this time, several modifications to the electrical wiring harness were made, and mechanical modifications to some of the payloads were required to fit the payloads into the very tight confines of the MightySat I spacecraft. At the completion of payload integration, an integrated systems test and a functional test were performed to verify the space vehicle's performance.

Several tests required by the NASA safety process were accomplished following payload integration. These included tests to verify the TIU and the satellite's startup sequence. An initial spin balance verified that the satellite's center of gravity was within the 0.5" envelope specified by NASA. The spin balance also attempted to lower the satellite's products of inertia to near zero. Because MightySat I is spin-stabilized using magnetic torque coils, the stability of its spin is highly dependent on its moment of inertia matrix. Large products of inertia produce a spin that decays quickly. Subsequent evaluation revealed that this initial spin balance process was inadequate to reduce the satellite's products of inertia to a low enough level. Late in the test flow, therefore, the spin balance test was repeated at the more capable Sandia National Laboratories spin balance table.

Vibration Testing

Following the initial spin balance testing, the satellite was readied for vibration testing. Four vibration tests were performed to verify the satellite's readiness for launch: sine sweep testing, random vibration testing, pyroshock testing, and sine burst testing. The simplest of the four tests was the sine sweep test, which subjected the satellite to a 0.5g frequency sweep from 20Hz to 2000Hz. The sine sweep test was used throughout vibration testing to verify the satellite's integrity. The sine sweep tests conducted during the sine burst testing also demonstrated the satellite's lowest natural frequency to be 51Hz, above NASA's minimum of 50Hz.

Random vibration testing subjected the satellite to the NASA-specified protoflight vibration profile, which simulates the launch vibration environment of the shuttle. Figure 7 illustrates the test setup for random vibration testing. To emulate launch conditions, the MightySat I space vehicle was secured to a non-flight version of the Hitchhiker Ejection System (HES), called the Milkstool, for the random vibration test. The Milkstool was secured to a Ling 4022LX vibration table using an interface plate, and the table's control accelerometer was situated at the base of this interface plate. The rest of the data, or auxiliary, accelerometers were distributed throughout the test assembly to measure the satellite's response to the random vibration profile. Following setup, the vibration test profile was executed in each of the three spacecraft axes, with functional testing and sine sweep testing conducted between each axis to check for structural or component damage. The MightySat I space vehicle sustained no damage during the random vibration test, in part thanks to the modifications made as a result of engineering model testing.

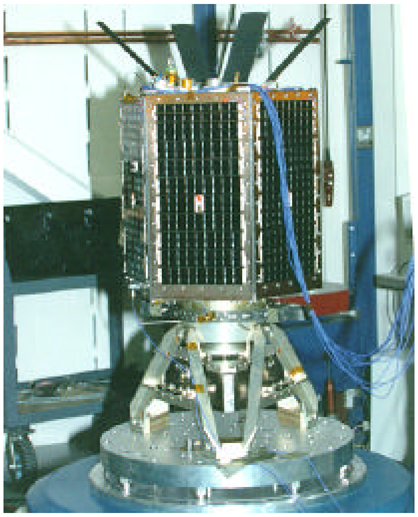
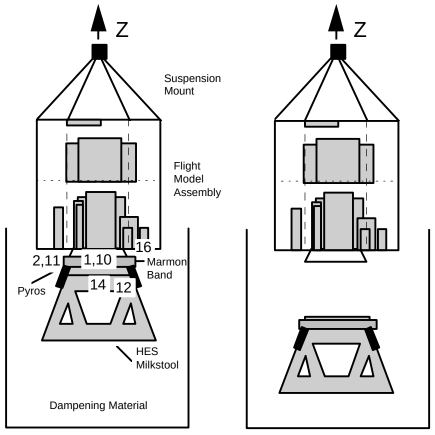


Figure 6: Random Vibration Test Setup



Pre-fire Test Assembly Post-fire Test Assembly

Figure 8: Pyroshock Test Setup

After the successful completion of random vibration testing, the satellite underwent pyroshock testing. The pyroshock test was designed to verify that all satellite components could withstand the shock produced by the ejection system's pyrotechnic boltcutters. Figure 8 illustrates the test setup for pyroshock testing. The HES Milkstool, without its ejection spring, was secured to the MightySat I space vehicle as if for flight, with a marmon ring, bolts, and two pyrotechnic boltcutters. The entire test assembly was suspended over a catch box lined with dampening material. The internal accelerometers from the random vibration testing were left in place to measure the shock produced by the boltcutters as it propagated through the satellite. MightySat I underwent two ejection simulations. The NASA Standard Initiators (NSIs) for the first ejection simulation contained 125% of the standard charge; during the second ejection simulation, the NSIs contained 85% of the standard charge. Figure 9 shows the shock response spectra measured by several of the accelerometers. Following each of the simulations, a visual inspection documented proper HES release and no spacecraft damage. A lights-on test verified proper spacecraft operation.

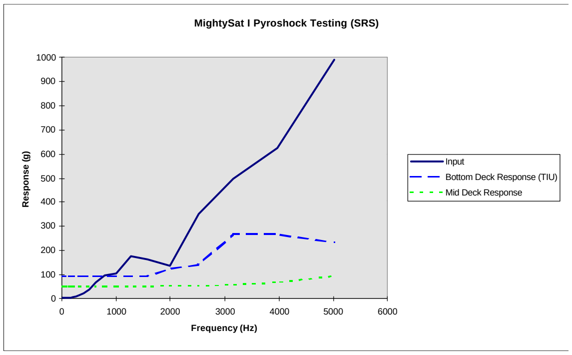


Figure 7: Shock Response Spectra

The final structural test was a sine burst strength test. NASA Hitchhiker safety requirements dictate that composite structures cannot be strength qualified through analysis alone. Therefore, MightySat I was required to undergo a sine burst test to verify its ability to withstand worst-case shuttle launch and landing loads. To accomplish this, MightySat I was secured to the vibration table using a low mounting fixture. The vibration table imparted a low-frequency (17 – 25 Hz) sine wave to the base of the fixture. At low frequencies and large deflections, the force imparted to the base of the satellite reaches values greater than 25g's. Amplification in the satellite structure increases the force seen by different parts of the structure; as a result, portions of the satellite experienced forces in excess of 40g's during the sine burst strength test. The sine burst profile was executed in each of the three spacecraft axes, and followed by sine sweep testing and satellite functional testing. MightySat I survived sine burst testing in all three axes, proving it capable of handling worst-case shuttle launch and landing loads. Some restaking of internal components, however, was required to reduce destructive force amplification on these components. Again, the experience gained in the engineering model testing proved invaluable.

Thermal Vacuum Testing

Following structural verification, MightySat I underwent thermal vacuum testing. Thermal vacuum testing assessed the satellite's ability to operate in the launch environment, and addressed NASA safety concerns regarding the satellite's battery. The MightySat I space vehicle was subjected to temperature extremes ranging from -20^{o} C to $+40^{o}$ C in order to thermally stress the spacecraft. A thermal vacuum functional test was conducted at each temperature dwell and during the temperature ramps. This functional test validated the MightySat hardware and software by functionally exercising all of MightySat I's subsystems. All basic normal and abnormal modes of spacecraft operation were run during the thermal vacuum functional test.

Each thermal vacuum functional test consisted of two parts. The first part, based on the plan for early orbit checkout, initialized and exercised all normal operations of the spacecraft, much as they would be exercised in early orbit. Following this checkout, the satellite was allowed to run in its nominal on-orbit configuration for a period of time. This period of nominal operations was normally conducted during the ramp from one temperature extreme to another. The second part of the thermal vacuum functional test exercised several off-nominal operations. Figure 10 is a graphical representation of the thermal vacuum test approach.

Several software problems were uncovered during the extensive functional testing that accompanied thermal vacuum testing, but none of the problems arose out of the thermal vacuum conditions themselves. The satellite's start-up circuitry functioned properly during two cold boots and two hot boots. The cold boots also demonstrated the functioning of the satellite's battery heaters. During the thermal vacuum testing, two of the SMARD devices were also fired, but the fires were unsuccessful. This prompted a several-week reevaluation and redesign of the SMARD experiment, which occurred after the mission sequence test. The ground failure of the SMARD experiment also prompted a redesign of the shape-memory devices by the payloader.

Mission Sequence Testing

The mission sequence test exercised MightySat I's ability to function operationally. This test, virtually impossible for anything but a small satellite, consisted mainly of a five-day, completely plugs-out functioning of the satellite. Figure 11 is a photograph of the setup of the mission sequence test. The MightySat I satellite was mounted to a spin table, with the satellite's Y-axis (its nominal spin axis) pointing up. The spin table was set to rotate at three revolutions per minute, MightySat I's nominal rotation rate. A Xenon lamp was used to illuminate the satellite's solar panels, and the satellite's ground equipment was set up a short distance away. A small antenna was attached to the operational RF ground station rack to receive RF signals transmitted from the satellite, and to uplink commands to the satellite. The signal from both the uplink and the downlink paths was attenuated at the ground station to simulate nominal predicted link margins.

Figure 10: Mission Sequence Test

After setup and initial testing, the MightySat I satellite was taken through its startup sequence. A pusher plate was used to hold the TIU microswitches closed, much as the HES ejection system would hold them closed in the shuttle cargo bay. After a short countdown, the pusher plate was removed, releasing the microswitches. The Xenon lamp was turned on, causing the photodetectors built into the startup inhibit system to sense the "sun". Test conductors then waited for the first telemetry from the satellite. Following satellite acquisition, MightySat I's early orbit checkout procedure was executed. When the command to initiate

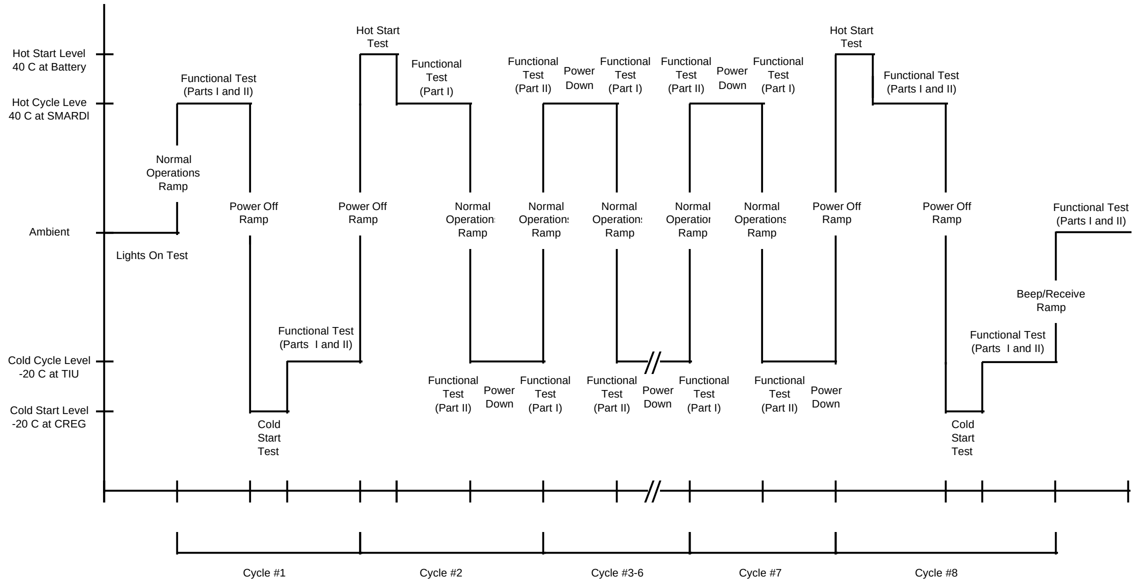


Figure 9: Thermal Vacuum Test Profile

the satellite's spin-up procedure was sent, the spin table was turned on to spin the satellite. Throughout the test, the Xenon lamp was turned on and off to simulate the satellite's normal sunlight-shadow orbital cycle. All satellite power was generated by the solar panels from the illumination of the Xenon lamp. All satellite commanding, and all telemetry downlink, was radiated through the air using the satellite and GCS RF systems.

Following the early orbit checkout procedure, MightySat I was placed in its nominal operating state, with the MAPLE, MPID, and solar cell experiments on and collecting data. Satellite contacts were scheduled periodically. The Xenon lamp was cycled on and off at the appropriate times to simulate sunlit and shadowed portions of the satellite's orbit. The satellite was allowed to run in this state, generating its own power, for five days. In this way, MightySat I was exercised in as close to on-orbit operational conditions as possible, greatly increasing the team's confidence in its ability to function on-orbit. The team that would operate the satellite in space practiced building commands, conducting satellite passes, and downloading telemetry as they would during on-orbit operations.

The Mission Sequence Test completed the KAFB portion of MightySat I integration and test. Following the SMARD repair, abbreviated vibration, thermal vacuum, and mission sequence testing was conducted to verify that the satellite had suffered no damage and that the SMARD experiment was now functional. Then the satellite was readied for shipment to NASA's Goddard Space Flight Center (GSFC).

LAUNCH PREPARATION

At GSFC, MightySat I underwent testing at specialized facilities unavailable in Albuquerque. An anechoic chamber was used to measure the satellite's antenna pattern in the final spacecraft configuration. GSFC's magnetic test facility, which is capable of generating rotating magnetic fields, was used to check out the satellite's attitude determination and control system (ADACS), uncovering several ADACS software bugs. The satellite was secured to NASA's Hitchhiker Ejection System and placed in the lidless canister that would mount to the side of the shuttle's cargo bay. The satellite's battery was charged, and an inhibit verification test was performed prior to the satellite's shipment to Kennedy Space Center (KSC).

Upon arrival at KSC, final functional testing was conducted on MightySat I. The satellite was installed into the shuttle's cargo bay at the Orbiter Processing Facility. During a battery charge procedure following the satellite's installation into the shuttle cargo bay, and fastener from a piece of NASA-provided GSE was discovered to be missing. This necessitated a removal of MightySat I from the shuttle cargo bay, so that technicians could inspect the ejection system for the missing fastener. NASA was concerned that should the fastener lodge in the satellite's ejection system, it could interfere with ejection, leaving MightySat I in a partially ejected state. This would be a considerable safety risk. The fastener was never found; however, the visual inspection determined that the fastener had not compromised the ejection system. The MightySat I canister was reassembled and reinstalled in the shuttle cargo bay.

While STS-88 awaited launch, MightySat I technicians performed three battery top charge and inhibit verification procedures on the satellite in the shuttle cargo bay. The last two tests were performed on the launch pad itself, and the final procedure was executed less than a week before launch. These tests verified that MightySat I's startup inhibit circuitry, required by NASA Safety, had not been compromised in the days leading up to launch. The procedures also charged MightySat I's battery.

In parallel with these efforts, MightySat I's operational team was also preparing for launch. Three intensive mission operations rehearsals were conducted to exercise the team's operational procedures. Data from satellite testing was massaged using special software to simulate real on-orbit telemetry. Simulated passes were conducted, the results observed, and follow-up actions orchestrated. During some of the rehearsals, satellite anomalies such as spacecraft resets and thermal problems were simulated. As a result of these rehearsals, many of the operational procedures were refined or re-written.

LAUNCH AND EARLY ORBIT CHECKOUT

On December 4th, 1998, the Space Shuttle Endeavor lifted off from Kennedy Space Center to begin STS-88. During the deployment of the Unity module, and during its linkup to the Russian Zarya module to form the first elements of the International Space Station, MightySat I remained in the shuttle cargo bay. During one of the flight's many extravehicular activities, an astronaut accidentally grazed the side of one of MightySat I's four paddle antennas with his foot. After inspecting pictures and videotapes of MightySat I during and after the accidental contact, MightySat I engineers determined that the encounter had not damaged MightySat I in any way. Therefore, ten days into the mission, the way was clear for MightySat I to eject.

The shuttle crew ejected MightySat I about ten days into the shuttle's mission, at approximately 1900 hours Mountain Standard Time (MST) on the 14th of December, 1998. Based on the satellite's predicted orbit, the first satellite contact was expected to occur at the KAFB ground station approximately 2.5 hours following ejection. Closer examination of the satellite's visibilities, however, revealed a low-elevation (approximately three degrees) pass over the Dulles ground station about an hour after ejection. The decision was made to point the Dulles antenna toward the low elevation pass and listen for satellite telemetry. At approximately 2000 hours MST on December 14th, the first telemetry from MightySat I was received at the Dulles ground station.

The initial telemetry from MightySat I indicated a healthy satellite, with a good battery state of charge and a good thermal profile. The satellite was in its initial startup mode, called "beep/receive." In this operational mode, the satellite transmits its routine telemetry to the ground every minute, and then listens for a response. Because the satellite initiates all contacts, this increases the chances that successful contact will be made with the ground station.

Initial attempts to upload commands to MightySat I were unsuccessful, due to RF interference and doppler correction problems with the ground stations. By the end of the first sequence of passes, however, an uplink to the satellite was achieved. MightySat I was left in beep/receive mode during the 12-hour outage when the satellite remained out of view of both ground stations. During this 12-hour outage, modifications to the ground stations were made to make it easier to contact the satellite.

During the second group of passes, more successful contacts were made with MightySat I. The picture of the satellite's state of health was refined with the first few dumps of the satellite's complete telemetry. A rudimentary communications schedule was uploaded to the satellite, taking it out of beep/receive mode. The solar cell experiment was activated at a low rate, to characterize the power generation of the satellite, and a magnetometer data collection was run to identify the satellite's spin profile. The solar cell and magnetometer data indicated healthy power generation, and a satellite wobbling predominantly around its "Z" axis approximately once per minute.

At the start of the third group of passes, ground controllers set the satellite's clock and briefly functioned the satellite's attitude control system for the first time. The Microparticle Impact Detector experiment (MPID) was also powered on during the third set of passes. The forth and fifth days of satellite contact were devoted to functioning the satellite's attitude control system. Several short, 20-minute functionings of the ACS were interspersed with solar cell and magnetometer data collections, as the mission control team evaluated the effect of each functioning on the attitude and spin of the satellite. Finally, on the fifth day after launch, the ACS was run for a full hour. Following this series of activations, the satellite was determined to be spinning in its nominal orientation around the Y axis, with a period of about 35 seconds.

Ground controllers sent a command to MightySat I to change its battery charging characteristics on the sixth day of operations. Temperatures measured at the satellite's battery were nearing 40^{o}C, high enough to cause degradation to the battery over the long term. Changing the satellite's Taffle curve setting allowed more power to be left on the satellite's solar arrays, and caused a dramatic drop in the battery's temperature, with only minimal impact on the battery's voltage. With the battery's temperature stabilized, the way was clear to turn on the MAPLE-1 experiment on the seventh day of satellite operations. This completed MightySat I's early orbit checkout. SMARD, the one remaining experiment, would not be functioned until six months into the mission.

Despite ground station problems, the MightySat I early orbit checkout was completed in seven days, several days earlier than expected. Over the next several weeks, MightySat I engineers would track down the ground station problems, allowing operations to become fully autonomous by the end of January 1999. Since that time, all MightySat I's payloads have been functioned, and months of on-orbit data has been collected.

MIGHTYSAT I EXPERIMENT RESULTS

Advanced Composite Structure

The Advanced Composite Structure, which serves as the structure for the vehicle, has no real data or command interfaces with the spacecraft. The structure, developed by Composite Optics Inc. under an Air Force Research Lab contract, consists of a composite frame, three decks, and seven solar panel substrates, as shown in Figure 2. The composite material used throughout the structure is a prepreg of K1352U graphite fiber with a 954-3 cyanate-ester resin. The spacecraft frames were fabricated by using a SnapSat™ approach[1], in which the elements are cut from cured flatstock layups and fitted together using a mortise & tenon technique. In addition to the well-documented weight savings of composite structures, the SnapSat™ approach reduces fabrication time by as much as 40%, and introduces greater flexibility in the process of design and fabrication of the spacecraft structure. The electrical resistivity of the structure is comparable to metallic designs, and only straps to ground the solar panels to the frame were necessary.

Pertinent data on the structure was acquired in ground testing, and particularly during the vibration testing designed to strength qualify the structure for flight on the shuttle. During early engineering model tests, a few of the metal spools used to secure the satellite's components to the composite structure broke loose under vibration and sine burst loads. The composite structure was reinforced and tested again, this time passing all structural verification testing. By surviving ground testing and satisfying all of NASA's safety requirements, the composite structure was verified as a viable structural platform for small satellites. MightySat I, however, actually required additional weight to increase its ballistic coefficient, and therefore the weight savings introduced by the composite structure was not necessary. Future small satellites may wish to trade the weight savings against the difficulty of navigating the launch safety process, particularly for shuttle secondary payloads.

Advanced Solar Cell Experiment

The Advanced Solar Cell Experiment (ASCE), the second Experimental Bus Component, provides all the power generation for the MightySat I spacecraft. MightySat I is one of the first space missions to use dual-junction solar cells, which offer a 15% performance gain over conventional GaAs cells. The dual-junction cells have a layer of Gallium Indium Phosphide (GaInP), which captures and converts shorter wavelength solar energy, relative to GaAs. The longer wavelength energy passes through the GaInP layer to be converted to electrical power in the underlying GaAs layer. Dual-junction cells can provide power at an average efficiency of over 21%, compared with 18-19% efficiency of GaAs cells and 14-16% from silicon cells. They are also an important step toward triple-junction technology with the potential for over 25% efficiency. This advance in space power generation technology is critical for many power-intensive sensors of the future, and could be particularly enabling for small satellite missions, which are often power-limited.

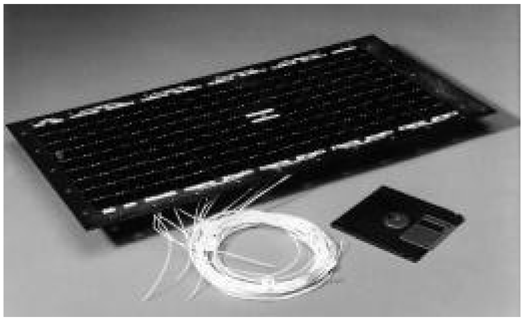


Figure 11: ASCE Side Panel

The ASCE payload consists of 13 strings of 40 GaAs cells (2x4 cm) and 6 strings of 18 GaInP cells (2x2 cm). A side panel, with one string of dual-junction cells and two strings of GaAs cells, is shown in Figure 12. The cells are bonded directly to a kapton-coated, monocoque, composite substrate (0.060” thick). The use of both solar cell technologies on the same mission provides a side-by-side comparison of cell performance on-orbit. The solar panels have been extensively tested to characterize cell performance, both at the vendor site and at AFRL’s Space Power Laboratory. However, the ability of the ground-based solar simulators to match the precise spectrum of the sun is limited. Thus, one of the objectives of this experiment is to resolve uncertainties in the beginning-of-life modeling of the performance of the dual-junction cells. Another objective is to determine the effects of the space environment on the efficiency of the cells, although the MightySat I orbit and lifetime are not expected to produce large-scale changes in cell performance.

The Advanced Solar Cell Experiment (ASCE) has been collecting data since the second day of MightySat I operations. Each solar cell collection sample records the array voltage produced by the solar panels, the current from each of the satellite's solar array strings, and the temperature of each panel. In addition, each data sample records the satellite time, the satellite magnetometer readings, and the readings from the satellite's coarse sun sensors. In order to compare ground test data to the string performance on-orbit, several corrections need to be made. Foremost among these corrections are the ones for solar incident angle and earthshine. In the laboratory, each panel is carefully mounted perpendicular to the carefully calibrated light source. On-orbit, the panels receive light from the sun at many different angles, and are also exposed to solar energy that is reflected off the Earth. Using data from the magnetometers on the MightySat-1 spacecraft, ground processing allows a reasonably accurate estimation of the solar incidence angle and earthshine angle at the time of solar panel data collection. After making the needed corrections, the on-orbit performance of the solar cells can be directly compared to the ground test results. Results for the MightySat I solar cell experiment are still being calculated, but initial side-by-side comparisons of the GaAs cells and the GaInP cells indicate that the GaInP cells are producing approximately 6-8% more current per unit area than the GaAs cells.

MAPLE-1

The Microsystem and Packaging for Low Power Electronics (MAPLE) experiment is a demonstration of advanced microelectronics and electronics packaging techniques. The objective of this experiment is to provide the first on-orbit demonstration of the latest advances in low power electronics, and characterize their performance in the collective space environment. This space experiment is seen by AFRL/VSSE as the first unit in what is hoped to be a series of experiments designed to evaluate emerging electronics and packaging technologies in space. As in the case of the solar cells, the expected MightySat I environment is not stressing to electronics from a radiation perspective. However, gaining space heritage for any of the emerging electronics technologies provides a larger performance database for assisting in the transition of the technology.

The MAPLE-1 space electronics experiment fielded involved five separate primary experiments and one very exciting "add-on" experiment. The payload, shown in Figure 13, consists of six electronic boards or "slices" containing several advanced technology items. The Advanced Electronics Board (AEB) was developed to determine the differences between the response of a radiation hardened and a military grade field programmable gate array. The purpose of the experiment was to examine how the gate logic unit degrades with time-in-orbit. This was done by testing approximately 80% of the 20,000 gates (PLD equivalent gates) available on each of the arrays by using identical programs to setup software instruction sets and then measuring the errors at the output of the arrays.

The Packaging Reliability Board (PRB) was developed to evaluate the reliability of packaging used on the ATC04 devices, which are Sandia National Labs (SNL) designed test chips. The reliability was examined by measuring the frequency of eight oscillators housed in four ATC04 chips and determining how the electronics degrades with time-in-orbit. During laboratory tests the oscillation frequency dependence on temperature and bus power was determined (-0.07 MHz/^{o}C and +3.2 MHz/V respectively). The Solid State Recorder Board (SSRB) was designed to evaluate the performance of the High Capacity Spaceborne Memory (HCSM) SRAM module in a space environment. The HCSM is a 40 bit x 512K bit deep static RAM on a high-density 2D multi-chip package. The test involved writing various 40 bit word patterns to the memory (00H, FFH, 55H, AAH), waiting for approximately 30 seconds, and measuring the single bit upsets in memory locations.

Figure 12: MAPLE-1 Experiment

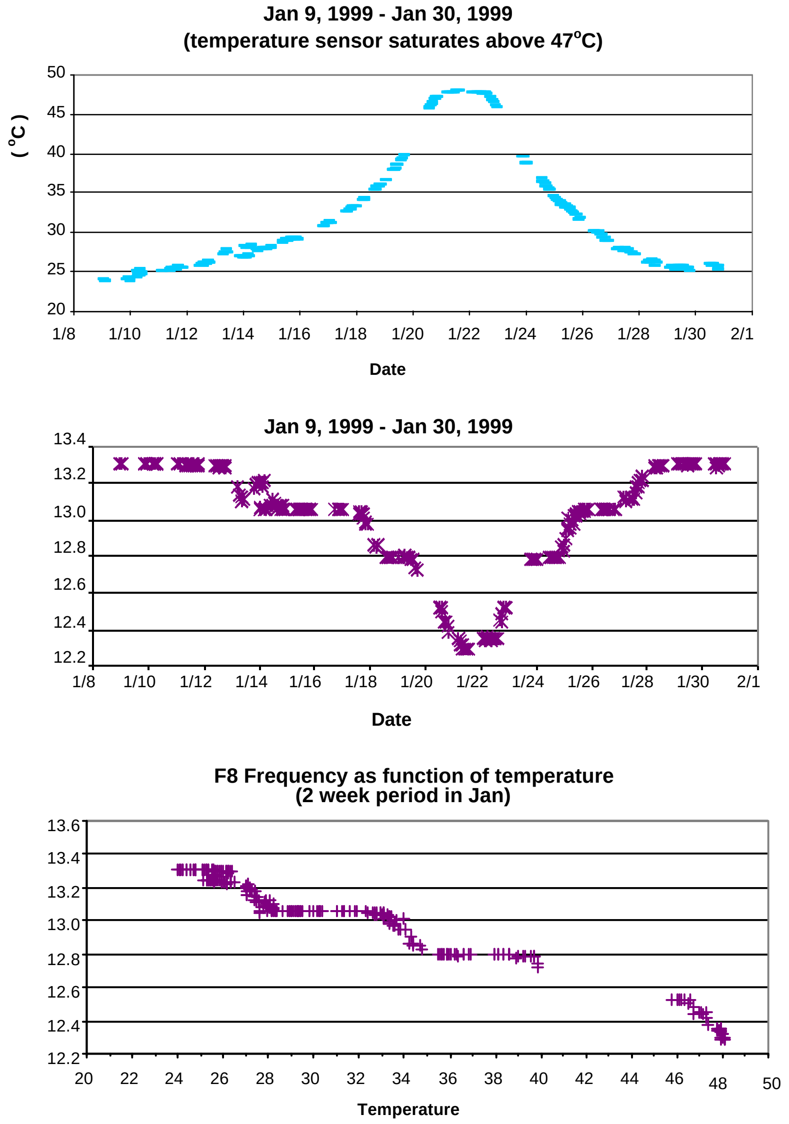
The Environment Monitor Board (EMB) was designed to measure the temperature inside the Maple-1 enclosure and the cumulative total dose radiation seen by the experiment during time-in-orbit. The Micro Electro-Mechanical Systems (MEMS) Evaluation Board (MEB) was developed to evaluate the electronics functionality of the MEMS device technology used to process the signals from 3-axis accelerometers. Two accelerometers were fielded on MAPLE-1, a local 5-g full scale unit and a remote 2-g full scale unit mounted near the Shaped Memory Actuated Release Device (SMARD) experiment. Electronic health tests were incorporated into the programs used to monitor the operation of the accelerometers as well as a "solenoid plunger" used to mechanically 'ping' the local accelerometer.

MAPLE-1 was powered on at 0800 Zulu time on December 21, 1998 and has been operating continuously since that time. All of the five experiments are in excellent health and are operating as expected.

Of the five experiments, the data from the EMB and the PRB experiments is the most interesting. This is because, for the AEB and the SSRB experiments, success means minimal errors - which is what has been observed to date. The single event upset (SEU) rate observed with the SSRB has been almost non-existent, but even with the limited data available a few observation can be made. A '00H' pattern written to memory is more likely to 'upset' than a 'FFH' pattern. Future efforts would want to determine if this pattern dependence is attributable to the layout of the memory gates on the chip -- or possibly is due to some other cause. The SEU rate is also expected to be independent of the physical location of the memory gate on the chip (the complete SRAM is composed of 4 separate chips mounted in adjacent locations on the support structure). Because of the low upset rate (low statistics), the dependence on physical location will be examined using the entire date set available at the end of MightySat's life-in-orbit.

The data from the "add-on" SMARD experiment is perhaps the most exciting. MAPLE-1 participation in the SMARD experiment involved measuring the response of the 3-axis MEMS accelerometer to the shock wave generated when a test "separation bolt" was fired. The SMARD firings consisted of four separate events. The MAPLE-1 remote accelerometer successfully captured the SMARD events and clearly showed the dramatic difference between the two types of devices. The shock from the two pyrotechnic devices propagated in three axes throughout the satellite mid-deck to all components located there. In contrast, the shock of the shaped memory devices was felt in only one axis, with the amplitude being several orders of magnitude less than for the pyrotechnic devices.

The next most interesting experimental result is the strange temperature dependence of the oscillator frequencies of the ATC04 chips. As the satellite permeates in its orbit, it moves from approximately 50% sun exposure to 100% sun exposure. As it does so, the satellite surface temperature increases. The temperature of the interior of the satellite, as measured by the EMB, follows the surface temperature. Figure 14a is the MAPLE-1 temperature over a two-week period in January. Figure 14b is the frequency of one of the oscillators (F8) over the same two-week period. Combining the two data sets, Figure 14c is a plot of the F8 oscillator as a function of the local temperature. Some observations can be made from this data. First, the overall temperature dependence (-0.05 MHz/^{o}C) is


Jan 9, 1999 - Jan 30, 1999
(temperature sensor saturates above 47^{o}C)

Jan 9, 1999 - Jan 30, 1999

F8 Frequency as function of temperature
(2 week period in Jan)

Figure 13: MAPLE-1 Oscillator Temperature Dependence

similar to that observed during ground testing (-0.06 MHz/^{o}C). Second, the plateaus observed were totally unexpected. The flat regions are where the oscillator frequency is independent of temperature, while the sloped regions (-0.16 MHz/oC) correspond to a very strong temperature dependence (almost three times the overall dependence!). Finally, the plateaus are all separated by 250 kHz and have almost the same duration in temperature (approximately 4^{o}C). This data has been made available to SNL, who are also puzzled by this rather bizarre temperature dependence.

Shape Memory Actuated Release Devices

The Shape-Memory Actuated Release Device (SMARD) payload is an on-orbit demonstration a new class of low-shock release devices. Such devices have application in nearly all space systems, and are essentially replacements for conventional pyrotechnic units. The SMARD devices are based upon a shape-memory alloy (Nitinol) which is used as the driving force to actuate the release of a fastener. Release devices in general are used to separate satellites from launch vehicle adapters, or to deploy antennae, solar arrays, sensor covers, or other elements of space systems. Studies have shown that the shock imparted on space systems from the firing of conventional release devices, such as pyrotechnic bolt cutters, can potentially damage sensitive electronics. Table 3 shows some ground performance data from the SMARD release devices, relative to commonly-used pyrotechnic and linkwire technologies. Shape memory Actuated (SMA) devices offer greatly reduced shock levels at the expense of slightly longer separation times. They are also relatively low-cost, and have the added benefit of being completely resettable. Thus, the specific flight unit can be ground tested to ensure functionality. SMARDs also offer reduced contamination and safety concerns, since there are no pressurized gases or explosion hazards.

Table 2: Comparison of Release Devices

Device	Shock (G's)	Separation Time (msec)	Resettable
Pyro	7000	2	No
Link Wire	5000	20	No
SMA Low Force Nut	500	40	Yes
SMA Two Stage Nut	200	30	Yes

The MightySat I SMARD payload consists of four release devices mounted to a common, instrumented deck, as shown in Figure 16. A neighboring electronics box performs the arming and firing of the devices, and routes the data collection channels to the spacecraft. The four release devices use different technologies to perform the release of a 0.25" bolt, which is captured in

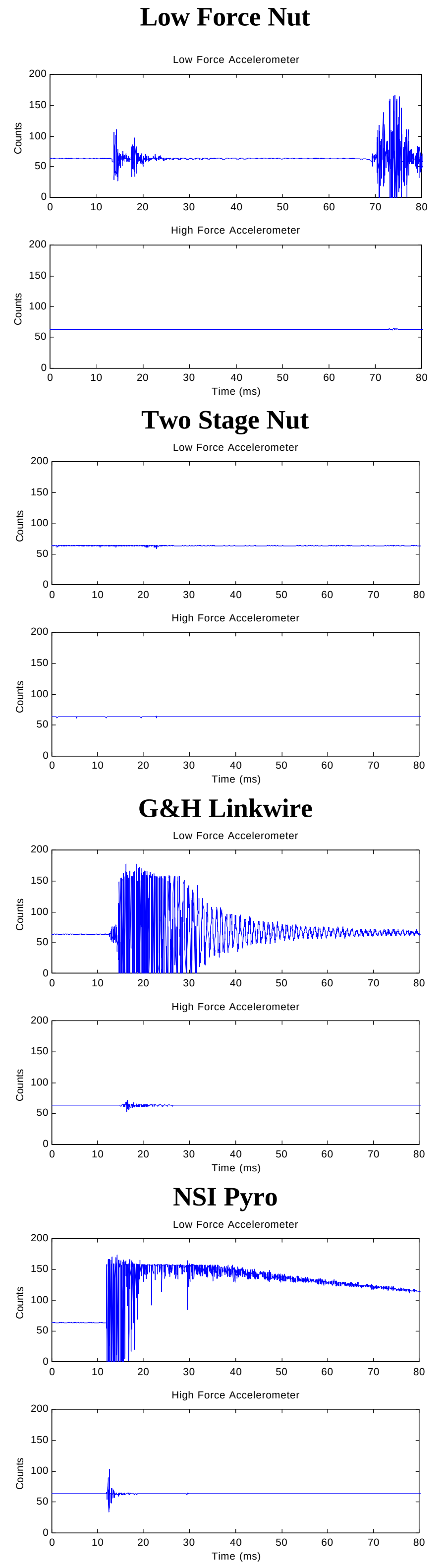


Figure 14: SMARD On-Orbit Data

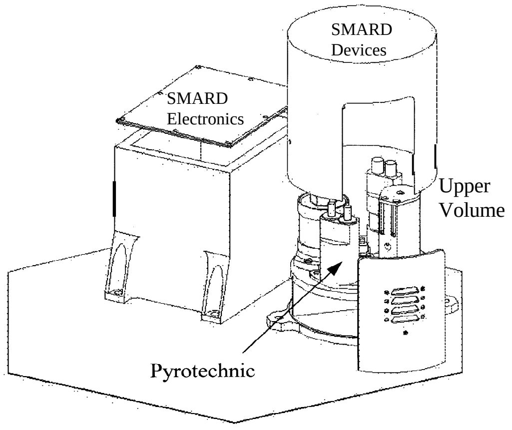


Figure 15: SMARD Devices and Electronics

the volume below the mounting deck. A conventional pyrotechnic device, a linkwire device, and two shape-memory actuated devices are used in this experiment. During the on-orbit actuation of the SMARD experiment in May 1999, the devices were "fired" one at a time, while actuation current & voltage, shock levels, release time, and temperature data were collected. The data was stored in spacecraft memory, and later downlinked to the ground for post-processing. Figures 15 shows the accelerometer data collected during the on-orbit actuation of each of the four devices in the SMARD experiment. Two accelerometers recorded each event. The first accelerometer was a low-force accelerometer selected to pick up the low shock levels generated by the shape memory devices. The second accelerometer was a high-force accelerometer chosen to pick up the higher shock levels produced by the standard release devices. During the NSI device fire, the low-force accelerometer saturated, producing the unusal graph shown at the bottom of Figure 15. While the data is still being analyzed, the plots show that the shape memory devices do present a significant reduction in the shock loads seen by the surrounding accelerometers. The MAPLE MEMS accelerometer also recorded data from the device actuations of the SMARD experiment.

The execution of the SMARD experiment by the MightySat I spacecraft presented several challenges. The release devices needed a 1200W burst of energy for actuation; delivering this power without affecting the spacecraft functionality or data collection required a specially-designed power system with a very capable battery. Fortunately, no adverse affects to the MightySat I vehicle were noted during the actuation of the SMARD experiment.

Micro-Particle Impact Detector

The MPID payload was a late addition to MightySat I, proposed just two months before shipment of the spacecraft to AFRL. The objective of this experiment is to measure direction and time of impact of spaceborne micron size particles with time of impact resolution of 0.1 s. By recording the time of impact and referencing to the vehicle ephemeris, the orbit position at time of impact can be determined. The objective of the overall MPID effort is to place as many detectors as possible into the space environment. These detectors can then contribute to the information database for natural and man-made orbital "debris."

The primary elements in this experiment are two Metal-Oxide-Semiconductor (MOS) discharge capacitor detectors that discharge upon hypervelocity particle impact. The detectors were developed by Prof. J.J. Wortman from North Carolina State University, and are capable of detecting particle sizes of at least 0.4 µm. Each MOS particle detector is 3" x 1-1/2" in size and approximately 0.013" thick, providing a total impact detection area of 3.7 in^2. Each detector is bonded to a detector holder assembly that is in turn mechanically fastened to the external bottom plate of the MightySat I spacecraft. The detector assembly and associated electronics weigh less than 0.4 lb. A particle impact causes an impact event record to be stored in the spacecraft control unit for later downlink. Each impact event record will store time of impact and output from two coarse sun sensors. Data from the coarse sun sensors is used to help determine the attitude of the spacecraft.

The MPID experiment was turned on during the first week of MightySat I on-orbit operations. To date, the experiment has recorded no impacts. Model data suggests that the lack of impacts may be due to the low impact detection area of this experiment, the spinning nature of MightySat I, and the relative scarcity of hypervelocity particle debris. MPID will continue to operate until the end of MightySat I's on-orbit life, however, and it is hoped that the detectors will measure an impact sometime in the future.

MIGHTYSAT I LIFETIME

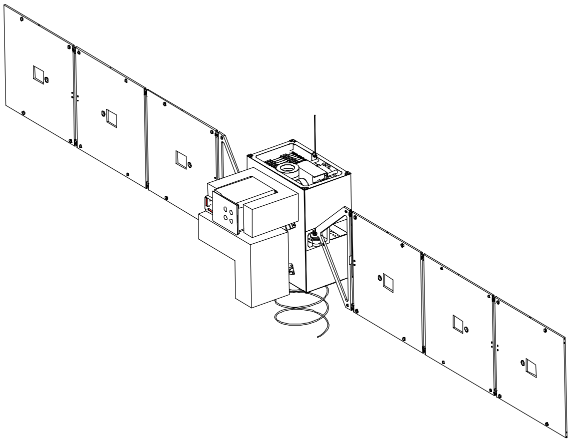
At this time, MightySat I is operating nominally. The Advanced Composite Structure has been demonstrated. The SMARD experiment, once operated, lies dormant. The MAPLE-1 and MPID experiments operate continuously, and the ASCE experiment is functioned at least once a day. Telemetry data continues to indicate a robust satellite, with no processor resets to date. Based on the satellite's orbital observations for the first several months of its operation, MightySat I is expected to reenter the earth's atmosphere in the early part of November 1999. This is just shy of its one-year on-orbit lifetime goal. The early reentry is predominantly due to the increase in atmospheric drag due to the solar sunspot maximum. Toward the end of MightySat I's lifetime, the rapidly-changing orbit may require more updates to the satellite's visibility schedule than can be reasonably accommodated. If this occurs, the satellite will be contacted less frequently, and will be placed in a quiescent mode between contacts to reduce spurious radiation by the satellite.

MIGHTYSAT II

As mentioned earlier, MightySat I is a single-mission pathfinder for the Space Vehicle Directorate's long term program for technology demonstration flights, MightySat II. As MightySat I was starting in June, 1995, a competition was being held to select a spacecraft contractor to develop 3-5 small satellite missions over the next decade. This contract was awarded to Spectrum Astro, Inc., a small satellite company in Gilbert, AZ with experience from the MSTI program. The program was initiated in March 1996, and the first satellite in the series, dubbed Sindri, was delivered to the Air Force for integration and test in April 1999. Launch of Sindri is scheduled for April of 2000, on board the second launch of OSC's Orbital/Sub-Orbital Program (OSP) launch vehicle.

A drawing of the MightySat II spacecraft is shown in Figure 17. MightySat II is a highly capable small satellite, which can perform a wide array of technology demonstration missions. Most notably, the spacecraft is twice as large as MightySat I, and is three-axis stabilized with deployable, articulated solar arrays. Some basic performance parameters for the MightySat II system are also shown in Figure 17. In some cases such as the downlink rate, reduced performance was accepted in order to maintain a low-cost approach. In other areas, however, such as attitude determination and control, the contractor was able to offer a relatively high level of capability at a reasonable cost. In this case, use of a flight proven OCA Star Camera, which has heritage from the Clementine small satellite mission, enabled a high performance yet low-cost attitude control system.

MightySat II is designed to host a large set of technology demonstration payloads, including earth-pointing or space-pointing sensors. Although volume, weight, and power limitations will still exclude large-scale payloads, MightySat II should be capable of supporting the needs of the large majority of AFRL technology developers. The MightySat II program will attempt to manifest as many payloads as possible on each MightySat II mission. The first mission features space demonstration of a Fourier Transform Hyperspectral Imaging system. Hyperspectral imagery is considered to have great potential for military applications, including characterization of soil conditions and detection of camouflaged targets. The MightySat II sensor, however, is strictly a technology concept demonstration, with no direct operational utility. This imaging system will stress the data collection and downlink capability of MightySat II, since it acquires 160 Mbytes of imagery data in only 8 seconds.



Vehicle Weight	275 lbs
Payload Weight	125 lbs
Maximum Power Generation	325 W
Payload Power Budget (sun/eclipse)	100/30 W
Attitude Knowldge/Control	0.15/0.25 deg
Uplink Rate/Downlink Rate	2/256 kbps

Figure 16: MightySat II Performance Parameters

Other follow-on technology demonstrations are in the area of composite structures. The MightySat II primary structure will use composite materials with built-in thermal management properties. Other structures demonstrations include a shape memory film that minimizes thermal distortion of solar arrays, a multi-functional film to transport power and data signals without cumbersome wire harnesses, and experimental solar array substrates using an isogrid design.

SUMMARY

This paper has provided an overview of AFRL's MightySat program, focusing primarily on the MightySat I mission. The primary objective of the MightySat effort is to provide a low-cost space-based platform for frequent demonstrations of advanced space system technology. Demonstration of emerging technology will expedite transition of advanced capabilities from the lab bench to operational Air Force space systems, which is a critical element of AFRL's charter. An overview of the MightySat I spacecraft was given. The satellite's integration and test process, launch and operations, and initial payload results were described in detail. A brief overview of the MightySat II effort was also included.

Perhaps the most notable features of the MightySat program are the focus directly on technology demonstration as a mission, and the attempt to execute a DoD small satellite mission in a new cost regime. Is MightySat "smaller, faster, cheaper, better?" MightySat seeks to build on the success of highly effective small satellite programs accomplished by the USAF over the past decade, including the STEP, MSTI, and REX series, RADCAL and APEX. These pioneering programs have built an infrastructure for the rapid development of highly capable small satellite missions at a greatly reduced cost. In some respects, these programs have paid the non-recurring cost of developing a government/industry environment where programs such as MightySat can succeed. In addition, international small satellite efforts have provided the models for performing very effective space missions at a fraction of what is typically spent on US DoD programs. In essence, MightySat represents an attempt to perform a USAF mission (technology demonstration) at a cost comparable to the scientific missions of our colleagues overseas. So how do we answer the above question? Relative to past USAF missions, MightySat I has been somewhat smaller, perhaps faster, and certainly cheaper. Since the MightySat mission of focusing strictly on technology demonstration is significantly different from that of past programs, judgment on “better” is not really possible. But the success of MightySat I is due in large part to those small satellite missions that preceded it.

ACKNOWLEDGMENTS

The authors of this paper would like to acknowledge the efforts of the larger MightySat Team. The efforts of these individuals have contributed to the progress of the MightySat program, and have directly or indirectly supported the development of this paper. The spacecraft development team at CTASS was comprised primarily of Mark Edison, Darrel Parks, Don Gibbons, Rich Kuha, Paul Devine, and Roy Jones with support from Paul Pendall, David Young, Rod Colen, Jeff Benton, Nancy Wharton, Dave Powell, Mike Moore, Jon Thurneysen, Karen Torrence, and Bill Evans. AFRL support within the MightySat Program Office was provided by Randy Kahn, Capt Rich Neufang, Lt Jacob Freeman, Pete Thomas, Joe Sciabica, Tammie Johnson, and Karen Ralston. Payload development for MightySat I was led by Capt Vickie Kennedy, Lt Dave Keener, Dean Marvin, John Nocerino, Lt John Paul, Alok Das, Ed Boyce, Bernie Carpenter, Jim Lyke, Todd Goforth, Patrick Serna, and Gary Liechty. Essential to the integration and test effort were Guy Robinson, Lou Nagao, Dale Stottlemyer, Jerry Kienle, Jim Hansen, Chris Mirate, and Chris O'Gorman. Aerospace Corporation technical support was provided by Mike Stallard, Mike Robyn, Bob Hosken, Frank Knight, Mike Werner, Boyd Carter, Bob Morse, and David Gilmore. MightySat I operations have been led by Lt Barbara Coop and Lt Valerie Malley, with support from Greg Saiz, Mark Martinez, Todd Giammo, Farrell Clark, Moroni Herrera, and Andrea Garcia. The NASA/GSFC team supporting MightySat I was Chris Dunker, Evan Goldstein, Mike Wright, Tony Martinez, John Pindrell, and Karl Schuler. Finally, the MightySat Program would have never gotten “off the gorund” without the efforts of Maj Mark Lutey, Col Mike Havey, and Sue Atwood.

REFERENCES

1. “Affordable Polymer Composite Structures for various Spacecraft Structural Components”, G.C. Krumweide, 9th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, September, 1995.