The MOST Microsatellite Mission: All Systems Go for Launch

Dr. Robert E. Zee
Manager, Space Flight Laboratory
Institute for Aerospace Studies
University of Toronto
4925 Dufferin Street
Toronto, Ontario, M3H 5T6
tel: 416-667-7864
e-mail: rzee@utias-sfl.net

Dr. Simon C. O. Grocott
Manager, Attitude Control Systems
Dynacon Enterprises Limited
3565 Nashua Drive, 2nd Floor
Mississauga, Ontario
Canada L4V 1R1
tel: 905-672-8828 x223
e-mail: scog@dynacon.ca

Dr. Jaymie Matthews
Associate Professor
Department of Physics and Astronomy
University of British Columbia
129-2219 Main Mall
Vancouver, BC, V6T 1Z4
tel: 604-822-2696
e-mail: matthews@astro.ubc.ca

Abstract

The MOST (Microvariability and Oscillations of STars) astronomy mission under the Canadian Space Agency's Small Payloads Program is Canada's first space science microsatellite, and is currently planned for launch in April 2003 aboard a "Rockot" launch vehicle. The MOST science team will use the satellite to conduct long-duration stellar photometry observations in space. A major science goal is to set a lower limit on the age of several nearby "metal-poor sub-dwarf" stars, which may in turn allow a lower limit to be set on the age of the Universe. To make these measurements, MOST incorporates a small (15 cm aperture), high-photometric-precision optical telescope developed by the University of British Columbia and a high performance attitude control system provided by Dynacon Enterprises Limited. As the launch date approaches, the MOST team continues to meet its goals. In addition to the original science objectives, the science team has determined that MOST can also be used to detect light from orbiting exoplanets for the first time. On the engineering side, all of the MOST flight hardware has successfully passed acceptance testing and integration of the spacecraft is underway. This paper summarizes the bonus science mission and discusses the unit and integrated spacecraft testing strategies of the MOST program. It summarizes the plan for spacecraft environmental testing and discusses post-environmental ground and on-orbit operations.

Introduction

The low-cost satellites that have now become known as "microsatellites" because of their small size and small budgets have always been experimental in nature. From the first satellites launched by AMSAT in the 1960's to modern-day university-led missions, microsatellites have not been traditional spacecraft based on radiation-hard parts, nor have they simply been space-qualified carriers for experiments. In the microsatellite world, the satellite *is* the experiment. While the original objectives were to serve as low-cost communication relays and to investigate and develop new radio techniques, microsatellites are now taking on new roles, including science missions. But even with these new roles, the satellite (its mission, its instrument, and its support systems taken together) *is still* the experiment.

The Microvariability and Oscillations of STars (MOST) microsatellite is Canada's first space telescope. Its mission is one of long-duration, ultra-precise stellar photometry, accomplished using a 15-cm aperture optical telescope mounted in a small suitcase-sized satellite bus. Recently, the MOST science team has determined that additional science return may be extracted from the mission, augmenting the original science objectives. This bonus science involves the detection of orbiting planets around other stars in our galaxy, or "exoplanets."

This bonus science (which does not require changing the design of MOST or its operational parameters) adds to the existing list of firsts embodied by the MOST mission. In addition to the advances in space astronomy, there are *technological* firsts that include 25-arcsecond, three-axis attitude control for a satellite of this class, and new electronics and computers to handle the operational requirements of the satellite. Admittedly, MOST "pushes the envelope" and breaks new barriers in microsatellite capabilities.

The MOST team has applied the microspace design philosophy to a challenging mission relative to currently available commercial technology, and has established an on-going capability to produce highly capable microsatellites for Canadians. This is a *programmatic* first for Canada and represents a bold pioneering spirit on the part of the Canadian Space Agency to launch low-cost experimental satellites at higher risk but with potentially higher returns relative to the investment made. Part of the microspace philosophy is redundancy through multiple missions versus multiple components on a single mission. Like dollar-cost averaging when purchasing units of a mutual fund, buying more missions when missions are cheap may result in greater returns by averaging down the cost of space science. Spreading an investment over several inexpensive focused missions instead of a single expensive mission with multiple objectives may, in some cases, result in more science for each dollar spent. The understanding is that the individual missions are developed the "microspace" way which some may interpret as meaning "developed at higher risk." The approach departs from tradition, however, and cannot be judged only against the standard metrics. Microsatellites are all about the courage to innovate with limited resources and good design practices. In keeping with that pioneering spirit, MOST is the first of these experimental satellites in Canada.

Bonus Science Relative to Original Mission

MOST is designed to detect rapid oscillations in the brightnesses of stars down to an unprecedented precision of a few parts per million. (An increase in apparent brightness of 1 ppm is equivalent to looking at a street lamp 1 km away and then moving the pupil of your eye 0.5 mm closer to it.) This will allow the MOST Science Team to translate subtle surface vibrations of nearby Sun-like stars into information about their internal structures and ages, through a technique known as stellar seismology. By targeting some of the oldest stars in Earth's vicinity of the Galaxy (a.k.a., "the solar neighborhood"), a lower limit on the age of the Galaxy, and by extension, the entire Universe can be determined.

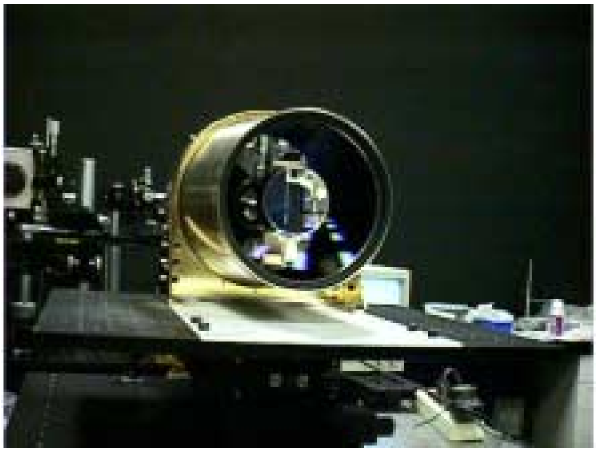

Figure 1: The MOST Telescope (15 cm Aperture)

The MOST Mission was originally designed around this primary science goal of rapid ultra-precise photometry. However, once the Instrument (Figure 1) was designed and under construction, and performance simulations were underway, it became apparent that MOST would be capable of another type of exciting science: the study of planets outside our Solar System.

Since the discovery of a planet around the solar-type star 51 Pegasi in 1995 [1], a new field of exoplanet research has blossomed. Various Doppler-shift surveys have identified over 100 candidates for exoplanetary systems at the time of writing. Most of these systems confounded the expectations of planetary astronomers. For example, nine of these exoplanets – which have masses comparable to or greater than Jupiter – orbit closer than 0.05 Astronomical Units from their parent star. (That would put them well inside the orbit of Mercury in our own Solar System, where no giant planet would seem to have any right to be.) Although the Doppler surveys give us the periods, sizes and eccentricities of the planets' orbits, and minimum values for the planetary masses, we have virtually no other knowledge of the nature of these mysterious worlds (Figure 2).

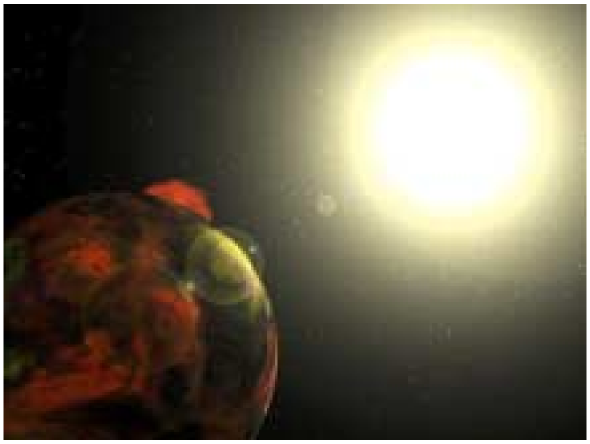

Figure 2: Artistic Rendering of an ExoPlanet.

Simulations (see Figure 3) by Green, Matthews, Seager & Kuschnig (2002) show that MOST will be sensitive to the variations in reflected light from these close-in giant planets as they orbit the star and change in phase of illumination (like the phase of the Moon). The variations have amplitudes of order 10 ppm, with periods of a few days. From the photometry collected by MOST of systems like 51 Pegasi and tau Bootis, the MOST Science Team will be able to deduce the radii and basic atmospheric composition of these planets.

In fact, the MOST Team is in a position to be the first humans in history to directly detect the light from a planet outside our Solar System. Like Galileo's pioneering observations of the phases of Venus, which revealed it to be his generation's version of an

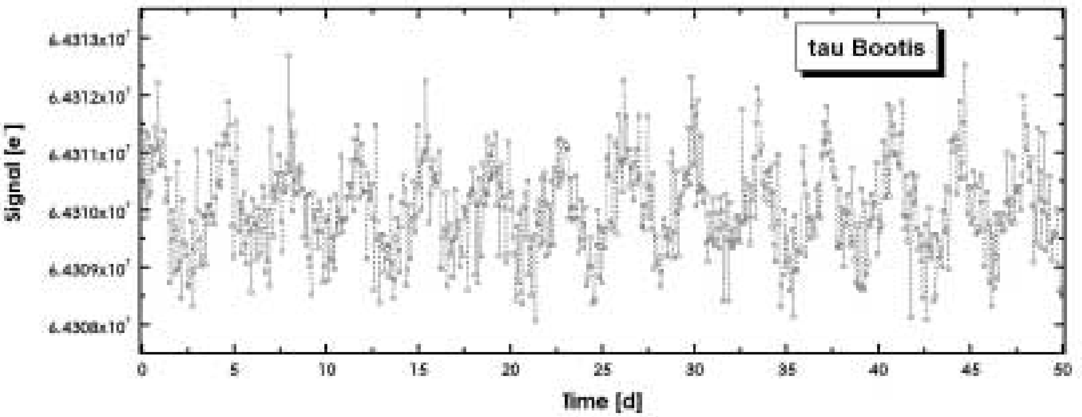

Figure 3: Simulated MOST "observations" of a star with an exoplanet orbiting every 3.3 days

"exoplanet" orbiting the Sun, data from the MOST space telescope (of comparable physical dimensions to Galileo's) promise to open a new frontier on our understanding of exoplanets.

Current MOST Satellite Design

The MOST microsatellite, as shown assembled at the Space Flight Laboratory in Figure 4, has several key subsystems in addition to the instrument. While these have not drastically changed over the last couple of years, they are worth summarizing briefly.

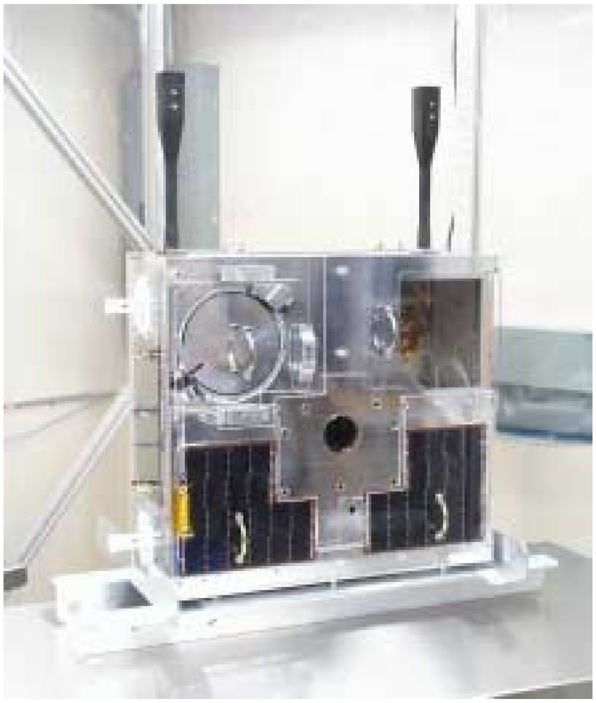

Figure 4: The MOST Microsatellite (with protective covers) in the Space Flight Laboratory Clean Room.

On-Board Computer Subsystem

There are five computers on board MOST as depicted in Figure 6. The housekeeping computer is an off-the-shelf product that has been modified to meet MOST requirements. Based on a V53 processor, the computer's crystal frequency has been increased from 9 MHz to 29 MHz to accommodate the processing demands of the mission. It interfaces with the rest of the satellite through a custom interface card that provides power, serial and digital I/O connections. The housekeeping computer's main tasks include receiving, executing, and distributing commands and/or files uploaded from the ground, and collecting and transmitting engineering and science data to the ground.

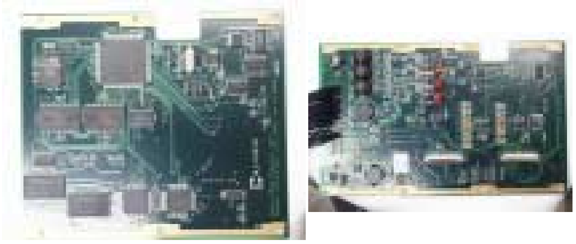

Figure 5: Attitude Control Computer in two parts – core computer (left), application board (right)

Four other computers are custom devices based on the Motorola 56303 DSP. Two are Attitude Control Computers (Dynacon "Micro-Nodes" – see Figure 5) to process sensor information and send commands to actuators based on high-performance control algorithms developed by Dynacon Enterprises Limited. One of the two attitude control computers is nominally a cold spare, activated only in the event of a failure. The remaining two DSP computers are for instrument control and data processing (Figure 7). They are connected to a pre-amp that is in turn connected to dual

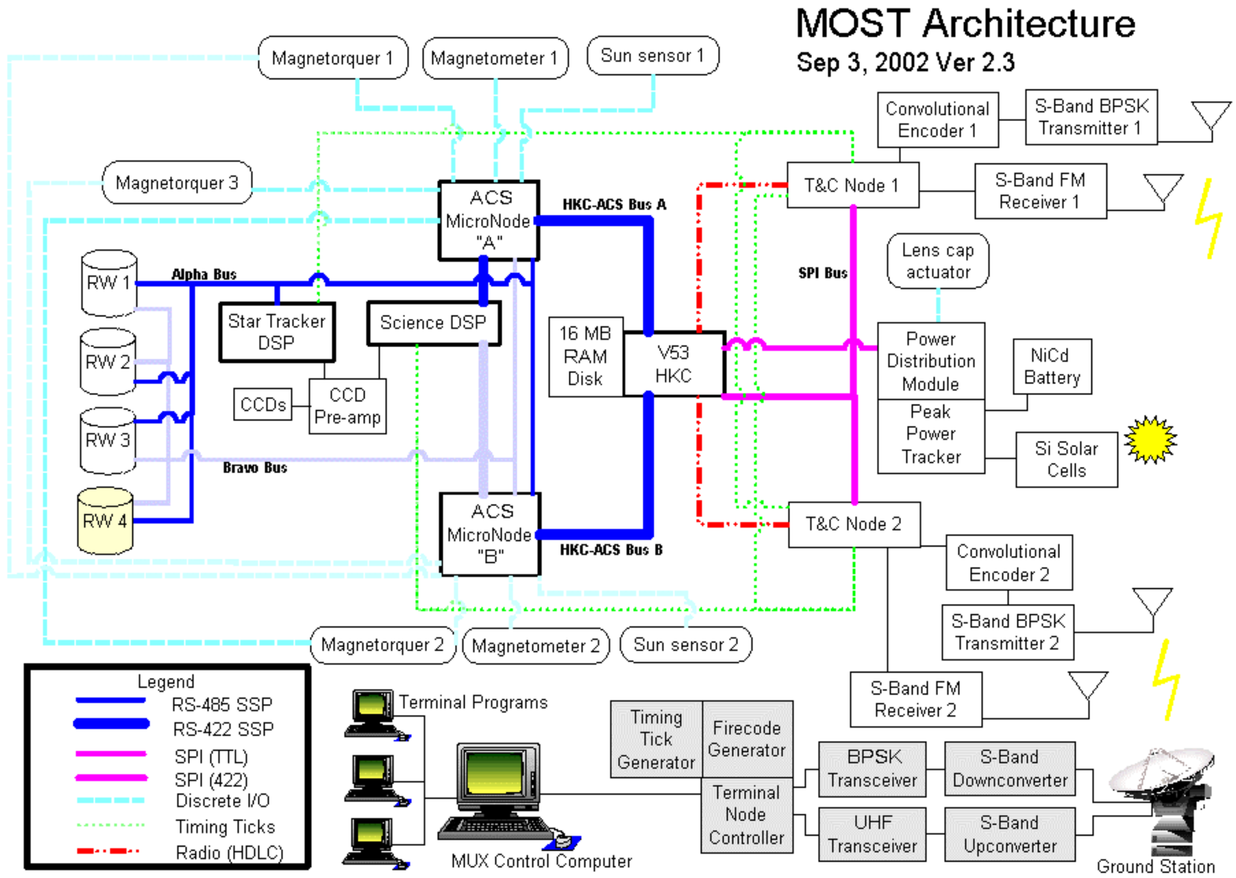

Figure 6: MOST System Architecture

1024x1024 CCD Arrays. One array is used in conjunction with Fabry lenslets to smear and stabilize the effect of image wander over the pixels of interest for science measurements. The other array is used for taking star images that can be used for star tracking. One instrument computer is dedicated to the science array while the other executes a star tracking algorithm and provides attitude errors to the active ACS computer. The instrument computers are designed to provide nearly noiseless CCD readings while tolerating disturbances from switching power supplies.

All computers have Error Detection and Correction hardware and software to correct for bit errors induced by radiation in the South Atlantic Anomaly. Single event latch-ups are corrected by power cycling the affected device.

Power Subsystem

The power subsystem is based on a centralized switching, decentralized regulation topology. Power regulation occurs through switching power supplies to maximize conversion efficiency (power is very limited in a satellite of this size – 35W in fine pointing operations and only 9W in safe-hold or tumbling operations). While this poses EMC/EMI challenges for the Science DSP computer that must read its CCD Array with almost zero noise, these challenges have been met.

The power system switches are controlled via the housekeeping computer. Two levels of load shed protect the satellite from unrecoverable battery drainage, allowing contingency operations to resume in safe-hold mode. All power lines have overcurrent protection.

In terms of energy storage, a NiCd battery provides power during eclipses and supports peak power draws from equipment such as the transmitters. High-efficiency silicon solar cells on all sides of the satellite generate energy to recharge the battery and provide power for fine pointing and safe-hold operations. Peak power tracking hardware and software (run by the housekeeping computer) maximize the available power to the satellite subsystems.

Figure 7: Instrument Computer (power supply shown in upper left)

Structure

The structure consists of aluminum trays that house the satellite's electronics, battery, radios, and attitude actuators. These trays are stacked (Figure 8), forming the structural backbone of the satellite. To this backbone, the science instrument, a 15 cm aperture Maksutov telescope is mounted with its barrel parallel to the axis of the stack. Six aluminum honeycomb panels, acting as substrates for solar cells and carriers for attitude sensors, enclose the tray stack/telescope assembly, forming the box seen in Figure 4. An actuated telescope door mounted on the star facing side of the satellite protects the telescope focal plane from direct stares at the Sun should the satellite tumble or lose attitude lock.

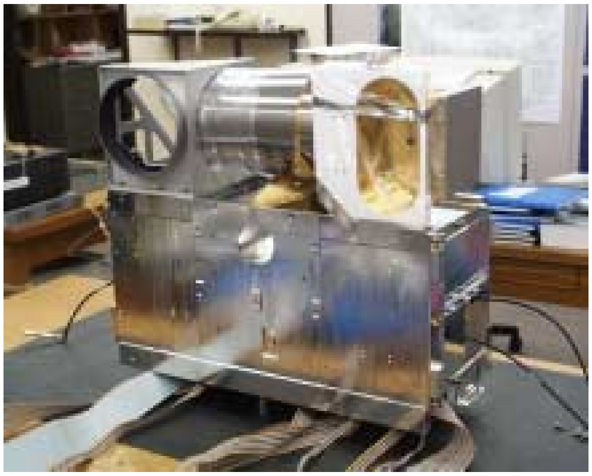

Figure 8: Tray stack (bottom) and telescope (top)

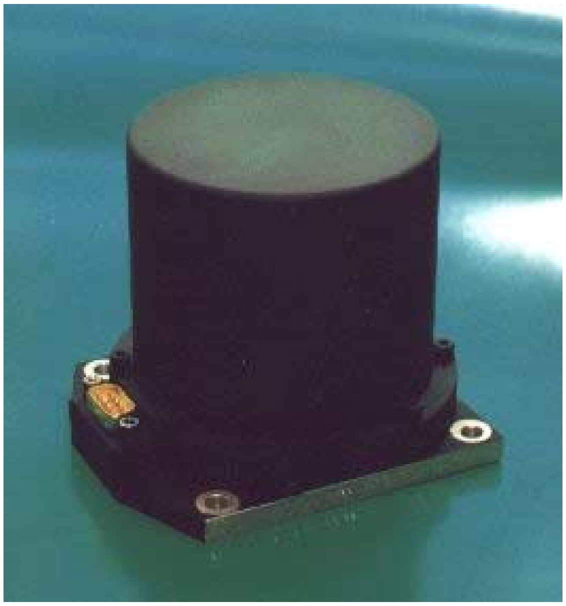

Figure 9: Miniature Reaction Wheel (Dynacon "MicroWheel")

Thermal

To ensure that components within the satellite operate at suitable temperatures, a combination of passive surface treatments are used including aluminum, gold, and silver teflon tapes. In the event that the satellite enters a cold state due to a disadvantageous attitude relative to the Sun, resistive heaters are used to keep the battery and trays sufficiently warm. During fine pointing operations, a passive radiator cools the telescope focal plane so as to minimize thermal noise in the CCD readout.

Attitude Control

The attitude control system consists of actuators, sensors and an attitude control computer running ephemeris models, an extended Kalman filter, and various control laws. The actuators consist of magnetorquers and reaction wheels (Figure 9), while sensors include magnetometers, sun sensors, and rate sensors. The solar arrays also contribute coarse sun sensing.

There are four attitude control modes for the satellite:

<u>*Safe-Hold:*</u> This is an uncontrolled state where the satellite could be tumbling or in some arbitrary attitude. In this mode, the focus is nominally on commissioning or recovery operations.

<u>*Detumbling:*</u> This mode involves using the magnetometers and magnetorquers to implement B-dot

control to slow the tumble rate of the satellite so that coarse pointing control can be executed. Normally this is used after kick-off from the launch vehicle, but can also be used in the event that the satellite is tumbling due to a reaction wheel momentum dump, for example.

Coarse Pointing: After the satellite is detumbled, the reaction wheels and sun sensors are incorporated to orient the main solar array towards the Sun and to roughly point in the direction of science interest. The magnetic control system is used for desaturating the reaction wheels.

Fine Pointing: After slewing to the target direction, the telescope is used as a star tracker to determine attitude to an accuracy of one arcsecond. In fine pointing mode, the reaction wheels and star tracking system are able to point the satellite at the target star with an accuracy of better than 25 arcseconds.

Communications

To communicate with ground stations located in Toronto and Vancouver, MOST employs two 0.5W RF output BPSK transmitters and two 2W FM receivers. All radios operate at S-band frequencies. The use of BPSK on the downlink allows MOST to stay under the Power Flux Density level recommended by ITU for non-interference with terrestrial systems. Sufficient downlink margin is maintained by using a 0.5 rate convolutional code, implemented on a custom board. On the uplink, FM receivers provide a simple, robust, and low-cost means to talk to the satellite. Both receivers and transmitters connect to custom telemetry and command nodes (Figure 10) that serve as modems and telemetry collection devices. To maintain omni-directional coverage, one receiver/transmitter pair is located on either side of the satellite, connected to quadrifilar antennas. Each radio operates on its own frequency. Thus, the appropriate transmitter is selected based on which receiver is being used.

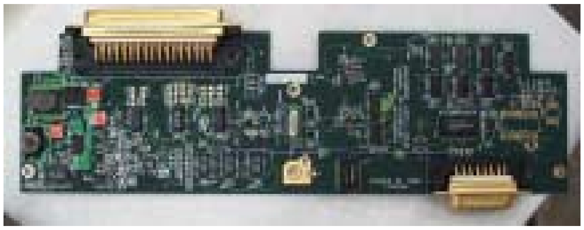

Figure 10: Telemetry and Command Node – modem and telemetry collection

Ground Stations

Two ground stations in Toronto and Vancouver will be used to download data from MOST. The main control station will be in Toronto, while the Vancouver station will be controlled and coordinated over the Internet. Although the mission can be accomplished with just one ground station, the second station increases the contact margin by 40%. There is also the possibility of a third station in Vienna that will provide even greater coverage.

The stations used for MOST communications are based on an amateur radio core station operating at VHF and UHF frequencies. They are upgraded with S-band transverters and BPSK transceivers connected to a 2-m parabolic antenna (downlink) and a 45 element loop yagi (uplink). The antennas are mounted on a heavy-duty, precisely controlled rotator located atop a 20-foot tower.

The ground station radios are connected to a custom terminal node controller (combination modem and serial communications controller) which is in turn connected to a computer that coordinates multiple terminals each running interface software for specific components on the satellite (see Figure 6). Through this system, terminal users have a virtual link to their satellite hardware of interest. The terminal node controller also generates “firecodes” or emergency commands to reset satellite hardware. A “timing tick” generator is used to maintain knowledge of clock drift in the instrument computers so as to accurately time tag science observations.

MOST Test Methodology and Results

Unit Acceptance Testing

To qualify units for space, a number of unit-level environmental tests were performed. These included thermal shock tests, operational thermal tests, and thermal vacuum tests using the thermal chambers and small vacuum chamber at the UTIAS Space Flight Laboratory.

The thermal shock test is mainly a workmanship test. The purpose is to verify that electronics have been assembled properly by subjecting them to high thermal gradients as they would see when transitioning between direct sunlight and eclipse. Before and after a thermal shock procedure, the unit is checked functionally at room temperature. Although this is an excellent means by which to mechanically test workmanship, not all defects (such as cold solder joints) may be detected until an operational thermal or thermal vacuum test is performed. A unit-level vibration test is normally not performed as the thermal shock test is taken as sufficient at this stage of testing.

An operational thermal test is performed after thermal shock testing to exercise units at temperatures they will see in space, based on the satellite thermal analysis. This test involves operating each unit at soak temperatures (nominally the temperature extremes expected) and performing cold and warm starts after transiting from survival temperature extremes. Operation during thermal cycling is also checked.

In cases that involve a custom or unqualified unit that is known to draw significant power ("significant" in relation to sensitivities revealed during thermal analysis), the operational thermal test profile is applied but under high vacuum conditions. The removal of convection as a heat transfer mechanism helps identify "hot spots" that may arise during operation and cause parts to operate beyond their specifications.

All MOST units have passed acceptance testing. Final burn-in functional testing will capture early component failures, if any.

Spacecraft Functional Testing

A spacecraft functional test plan covers all aspects of unit functionality but within the context of spacecraft-level operation. The complete test procedure is executed before and after major environmental tests, while a shorter procedure is used in other cases. In addition, based on early operations planning, the satellite is tested through all phases of expected on-orbit operation, as if it were in space. This is accomplished by in-the-lab exercises involving the ground station hardware and satellite communicating across a wireless link.

A limited amount of failure mode testing will occur to verify that no satellite "death modes" exist, i.e. that the satellite cannot hurt itself either autonomously or through ground command. This testing will be based on a documented failure modes summary. Contingency operations will be practiced to gain experience in dealing with component failures and to refine the contingency operations plan.

The attitude control system is verified by performing tests on an air-bearing table. Detumbling, coarse pointing, and fine pointing control can be validated in this way. High fidelity models of the attitude control hardware are used in a comprehensive simulation to predict, with confidence, the attitude control performance of MOST.

At present, MOST has passed its spacecraft functional test and detumbling and coarse pointing tests have proved successful.

Spacecraft Environmental Testing

At the spacecraft level, MOST will be environmentally tested at the David Florida Laboratory. The tests will include vibration tests using force-limited approaches developed and applied by both CSA and NASA. The random vibration profiles will incorporate additional loads representing the effect of acoustics.

Following vibration testing, a thermal vacuum test will be performed to verify the MOST thermal model and operate the entire system in as representative environment as possible. Operational tests for various attitude scenarios will be performed.

Finally, EMC tests will be performed to verify that the satellite will not be damaged by emissions from the launch vehicle. Conversely, MOST will be virtually off during launch and will not affect the launch vehicle. The separation switch monitor emissions are sufficiently low so as not to be a concern.

Burn-in Testing

The purpose of this testing is to weed out early component failures brought on by defects in parts manufacturing and/or damage induced by environmental testing at the unit or spacecraft level. To pass this test, all units must operate for a set period of time (does not have to be continuous) without failure or modification.

So far, burn-in testing is approximately 20% complete. Final burn-in testing will be completed after the spacecraft returns from the David Florida Laboratory.

Operations Plan

After kick-off from the Rockot Breeze stage, MOST will be commissioned using the Toronto ground station. All critical systems will be checked using predefined test scripts and all telemetry will be verified. Upon establishing the health of the satellite (including the charge on the battery), the primary ACS computer will be turned on and the detumbling algorithm will be executed. The reaction wheels will then be checked and then used to coarse point the satellite for maximum power. The instrument computers will be exercised and their clocks set and checked. Star images will be downloaded to aid in slewing the satellite to the target star of interest. With an uploaded star catalog, the telescope will then act as a science instrument and star tracker. Fine pointing operations will begin with science data streaming to the housekeeping computer for download to the ground.

Pre-positioned code will be present on PROM or Flash memory chips to allow quick loading and execution of application code. However, all application code can be uploaded from the ground if necessary (if there are bugs or if operation can be improved via new code). Uploaded commands and code will first be validated using a “flatsat command facility” – a duplicate set of satellite hardware, mainly flight spares – before sending these to the satellite.

Science data will be transferred in two streams, one representing the critical data needed, and a second stream to aid in the analysis. Should a communications outage occur, the critical data stream will accumulate for up to five days for eventual download to the ground. Although dropouts in science data can be tolerated, 90% observational coverage is required. Based on analysis this should be easily achieved despite possible radiation hits in the South Atlantic Anomaly.

A preliminary operations plan has been written and will be refined during the final burn-in testing of the satellite at the UTIAS Space Flight Laboratory.

Conclusion

The MOST microsatellite is an experimental satellite with capabilities that “push the envelope” of what currently can be accomplished with microsatellites in general. The combination of an ultra-precise photometer together with a 25-arcsecond accurate attitude control system will permit virtually uninterrupted stellar observations for up to seven weeks. This will allow astronomers to characterize the size, core composition and age of stars in our galaxy, and help set a lower limit on the age of the Universe. In addition, the astronomy team has discovered that additional science is possible in the form of detecting orbiting exoplanets.

The MOST team continues to meet its scientific and engineering goals. At the time of writing, the MOST microsatellite is on its way to the David Florida Laboratory for spacecraft environmental testing, having passed unit acceptance and spacecraft functional tests.

The launch of MOST in April 2003 aboard a Rockot launch vehicle will open a new era in Canadian space history, continuing the pioneering spirit of the third country in the world to go to space. MOST will be the first in a series of Canadian microsatellites, with a vision towards significant science return relative to investment. The microspace philosophy of multiple modest investments in experimental satellites developed with commercial components and good design practices may ultimately lead to more science per dollar than otherwise would be possible. With MOST, the Canadian Space Agency is demonstrating what it means to be a courageous pioneering innovator.

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