

# Canada's First Microsatellite – An Enabling Low-Cost Technology for Future Space Science and Technology Missions

Dr. Robert E. Zee

Manager, Space Flight Laboratory  
University of Toronto Institute for Aerospace Studies  
4925 Dufferin Street  
Toronto, Ontario, Canada M3H 5T6  
416-667-7864, rzee@utias-sfl.net

Peter Stibrany

Manager, Microsatellite Systems  
Dynacon Enterprises Limited  
3565 Nashua Drive, 2<sup>nd</sup> Floor  
Mississauga, Ontario, Canada L4V 1R1  
905-672-8828 x226, ps@dynacon.ca

## Abstract

*The MOST (Microvariability and Oscillations of STars) astronomy mission has been chosen by the Canadian Space Agency's Small Payloads Program to be Canada's first space science microsatellite, and is currently planned for launch in early 2002. The MOST science team will use the MOST 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 will incorporate a small (15 cm aperture), high-photometric-precision optical telescope developed by the University of British Columbia. The MOST mission does not only call for the expansion of the frontiers of science, however. There are a number of important technological firsts for Canada as well. A direct benefit of meeting the formidable challenges of the MOST mission is the creation of a versatile spacecraft bus that can be used for a multitude of science and technology missions that could not be performed previously using a spacecraft of similar size and cost.*

## Introduction

Canada's first microsatellite and space telescope, MOST (Microvariability and Oscillations of STars), is expected to break new ground both scientifically and technologically. While the world marvels at the astronomy, and the implications the scientific results have on our understanding of the universe, Canada will not only benefit from showcasing its scientists, but also from the expertise generated to enable future ambitious microspace missions at a fraction of the traditional cost. The MOST satellite bus and ground stations are currently being developed by Dynacon Enterprises Limited and the Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS/SFL), in collaboration with AMSAT. The modular spacecraft design may be applied to a wide range of future missions with varying requirements and degrees of complexity.

## MOST Mission

The MOST mission entails placing a low-cost satellite equipped with a high photometric precision telescope into Earth orbit (Figure 1), and using it to conduct observations on a series of stellar targets. The baseline orbit is a dawn-dusk sun-synchronous orbit, with 98° inclination at an altitude of about 785 km. To collect long-duration stellar photometry, the satellite must stay inertially pointed with better than half an arcminute accuracy and stability. The extremely demanding attitude

control requirements, the challenging data management tasks, and the implications these have on the thermal design of the satellite and the development of suitable electronics, has created a versatile microsatellite bus capable of accommodating the most challenging science objectives. The expertise developed at Dynacon and UTIAS/SFL can also be exploited in adapting the spacecraft design to the needs of the most ambitious space scientist. Moreover, the ground stations installed for the MOST mission can be used for many different missions, with customized interfaces tailored to specific mission requirements.

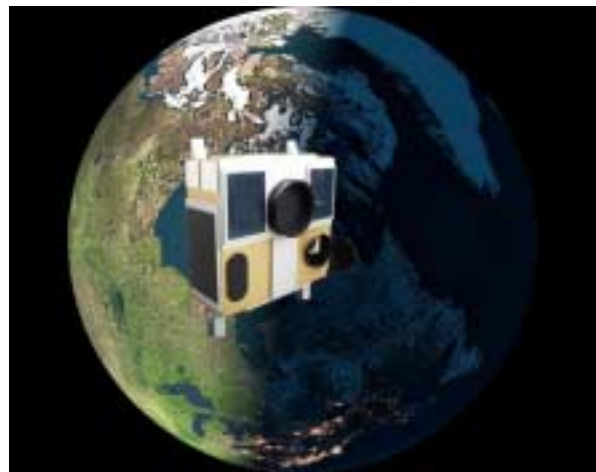


Figure 1: Depiction of MOST in Orbit

## Multi-Mission Microsatellite System Design

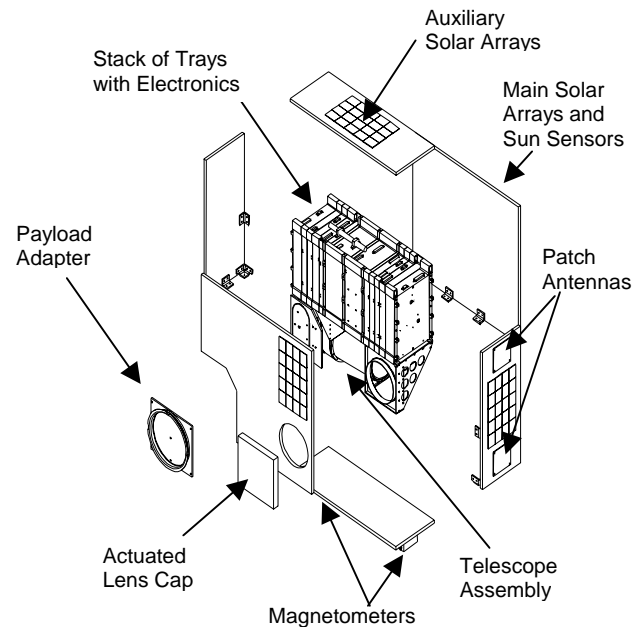
The equipment that has been developed to support the MOST mission comprises two major elements, the MOST Satellite and the MOST Ground Segment. The satellite is divided into a Bus and a Payload made up of Subsystems as shown in Table 1. The Ground Segment consists of two Ground Control Stations, one in Toronto, and the other in Vancouver.

**Table 1: Satellite and Ground Subsystems**

Primary Element	Secondary Element	Subsystem
<i>Satellite</i>	<i>Bus</i>	Structure
		Thermal Control
		Power
		Attitude Control
		Telemetry & Command
		On-Board Computers
	<i>Payload</i>	Instrument
		Payload Data Processors
<i>Ground Segment</i>	<i>Ground Control Stations</i>	Toronto Station
		Vancouver Station

The guiding philosophy for the design of this system is to employ proven microsatellite designs from some of the most experienced microsatellite designers in the world as a starting point, making adaptations to these in order to meet the core science objectives of the mission. The resulting system design allows the mission to be achieved while re-using structural, power, on-board computing, telemetry & command and ground station subsystem design envelopes from previous successful microsatellite missions. This in turn can be used for future microsatellite missions with ease.

The satellite's general layout is shown in Figure 2. It is driven by the secondary payload volume envelope provided by the Delta II launch vehicle. It incorporates a stacked set of Bus functional modules, with an adjacent Payload bay defined by a set of panels carrying solar arrays. The overall dimensions, including an allowance for the launch vehicle interface hardware, but excluding appendages for antennas and magnetometers, are approximately 63 by 58 by 25 cm.



**Figure 2: MOST General Layout**

### *Bus Overview*

The main features of the MOST Bus design are:

- It is based on the stacked-tray modular concept that has been used successfully in the AMSAT Microsat series of satellites, as well as in the University of Surrey/SSTL UoSATs. The main functional elements of each subsystem (electronics boards, reaction wheels, batteries) are housed within a set of trays of identical cross-section, which are bolted together to form a "box-beam" structural back-bone for the satellite.
- The stack of trays is covered by a set of structural panels, on which are mounted photovoltaic cells, patch antennas, magnetometer booms, and sun sensors.
- On one panel is mounted a standard Delta-II Payload Adapter Assembly (PAA): one-half of a Marmon-clamp system, the ring plus some supporting structure.
- The total mass of the microsatellite is approximately 50 kg, with first frequency of vibration above 100 Hz. The satellite structure has been optimized to withstand all launch loads with comfortable margins.

- The Power, Telemetry & Command, and On-Board Computers Subsystems are designed based on the same approaches and philosophies used to design similar subsystems that have been flown on other microsatellites.
- The On-Board Computer Subsystem is based upon a multiprocessor architecture involving an off-the-shelf V53 housekeeping computer communicating with custom DSP boards using the RS-422 standard. The Motorola DSP56303 is used in the Attitude Control Computers in addition to the CCD Drive Computers.
- The Telemetry and Command Subsystem consists of custom dual S-band receivers and transmitters, using GMSK modulation, and communicating with the AX.25 and PACSAT protocols. The transmitters have an efficiency of about 30%, much better than most off-the-shelf products available. A data rate of 9.6 kbps is available for the MOST uplink, while 38.4 kbps is used on the downlink.
- The Power Subsystem uses a centralized switching, decentralized regulation topology for maximum flexibility and control. The power supply to the satellite uses Peak Power Tracking to maximize the energy conversion efficiency of the solar arrays. The total available power from the solar panels during nominal operations is approximately 30 W.
- The Attitude Control Subsystem (ACS) uses as its foundation a design that has been used successfully in other microsatellites. Magnetometers and magnetorquers are used to provide a simple but low-accuracy basic attitude control capability for detumbling.
- To create the high-accuracy attitude control capability needed to achieve the science goals, a set of small reaction wheels provide three-axis actuation. These are commanded based on pointing error signals generated by the science instrument, when operating in fine-pointing mode. On MOST, the instrument also acts as a star sensor. This tightly couples telescope pointing with the performance of the Attitude Control Subsystem.
- The Thermal Control Subsystem is entirely passive, except for trim heaters that regulate the temperature of the CCD focal plane. This is no small feat considering that most previous microsatellites are spinning spacecraft with much less difficult thermal trade-offs. In addition, deployable solar arrays are not used, creating an even greater challenge.

- The dimensions, mass and available power have been tailored to the needs of the MOST mission. Depending on launch vehicle selection and mission needs, the dimensions, mass and power may be optimized differently.

### *Payload Overview*

The MOST satellite's payload comprises the science instrument, along with the electronics required to operate it and interface it with the on-board computers. The main requirements on the instrument are:

- To collect science photometry data from the selected target star. This is required to be photometrically very precise in order to maximize the signal to noise ratio, to be photometrically stable over sample runs of several weeks duration when subject to up to 25 arc-seconds of instrument boresight wander, and to have a wide dynamic range in order to maximize the number of useable target stars.
- To collect star-field image data with which the ACS will measure the instrument's pointing error. The baseline requirement here is to produce star field image data once per second, using variable exposure times of as little as 1/10 of a second.

The main requirements on the payload data processing electronics are to operate the instrument's camera, to process photometry measurements from the target star using variable exposure durations between 1 and 60 seconds, and to process the star-field image data at a 1 Hz rate with a maximum latency time of one second to produce boresight pointing error measurements with an accuracy of 1 arc-second.

The science instrument features a dual-CCD-based visible-light camera that receives light through the largest optical telescope that can fit within the available volume and mass allocations. The baseline design has a 15-cm aperture, and is about 55 cm long. A Maksutov optics design is used. The CCDs are passively cooled, but actively heated to control their temperatures and to maximize photometric precision.

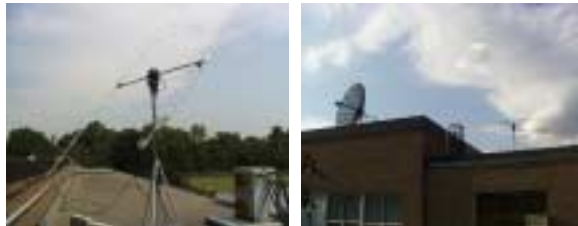
### **Ground Stations Overview**

A pair of ground control stations is planned, to issue commands to operate the satellite's payload, attitude control subsystem, and other housekeeping functions. The

stations are to be located at UTIAS/SFL and the University of British Columbia.



**Figure 3: Ground Station Equipment**



**Figure 4: Yagi and Dish Antennas**



**Figure 5: Virtual Link Command Interfaces**

Both ground stations are based on the same design: commercial UHF/VHF transceivers with programmable Doppler correction, L- and S-band up- and down-converters, and AMSAT-developed satellite tracking and radio-operation software running on commercial PC-class computers. These are inexpensive to develop and reliable

in operation, and have the data throughput capacity needed to downlink the data generated by the satellite's payload (Figure 3).

The antenna system consists of a collection of Yagi antennas for VHF, UHF, and L-band communications. Two and three meter reflector dish antennas are used to communicate at S-band at relatively high data rates for microsatellites, such as 38.4 kbps (Figure 4).

The inexpensive ground station architecture and system design is augmented by custom software used for remote ground station control over the internet. Specialized command interfaces have been written that talk to a coordinating program that organizes all requests into a logical command sequence for the satellite (Figure 5). Each command interface has a virtual link to the relevant hardware on board the satellite. To the user, it is as if the computer on the ground is talking directly to that hardware in space. These programs may be tailored to the specific attitude control and scientific payload requirements of any microsatellite mission.

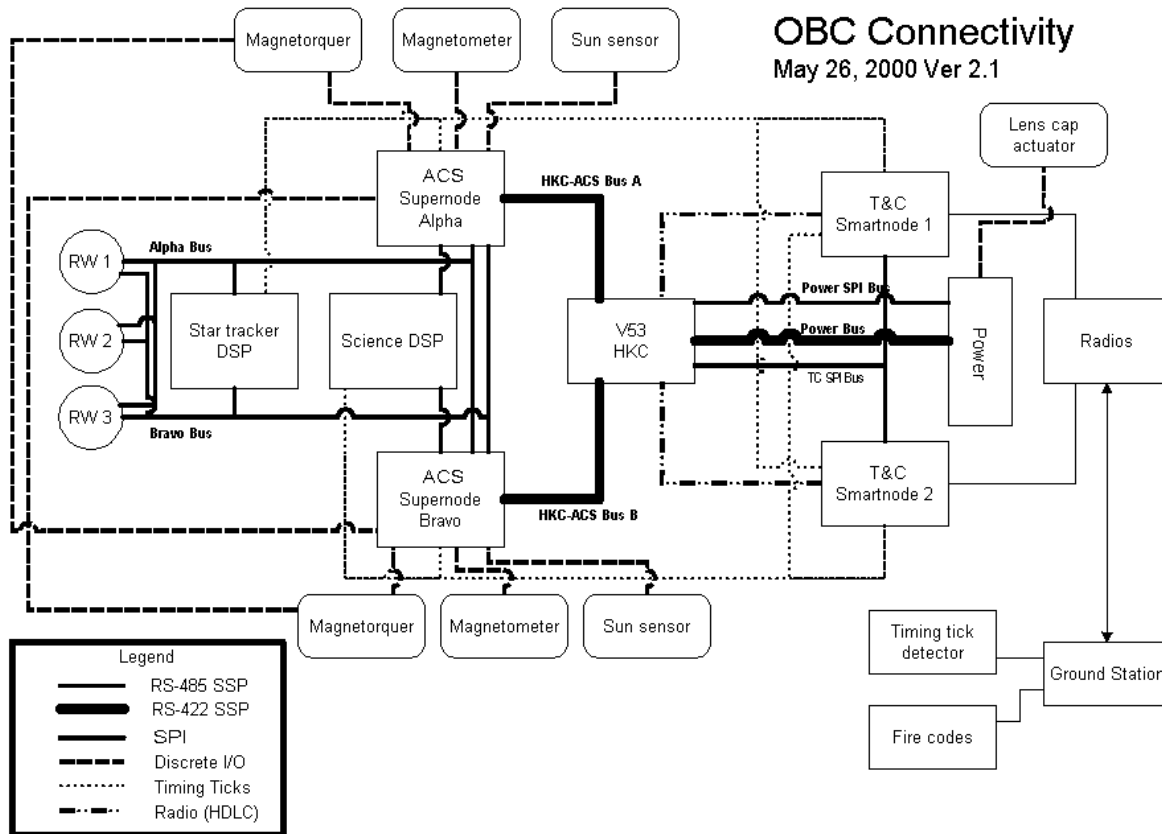
The entire ground station package is available to scientists, principal investigators, and general microsatellite users at a fraction of the traditional cost. For a few tens of thousand dollars, UTIAS/SFL can provide a complete functioning ground station at any desired location.

## Enabling Technologies for Future Missions

Several key technologies have been developed for future microspace missions. These are in addition to the expertise developed in creating optimized structures, thermal control systems, and high-efficiency power systems available at Dynacon Enterprises Limited and UTIAS/SFL. The technologies, together with the design expertise created by the MOST mission afford Canadians continued low-cost access to space for increasingly ambitious space science and technology missions.

### *On-Board Computers*

The On-Board Computer Subsystem for MOST is shown in Figure 6. An off-the-shelf V53 computer manages housekeeping tasks (including power and telemetry management) and communicates with the radios.



**Figure 6: MOST On-Board Computer Architecture**

The housekeeping computer is in turn connected to redundant Attitude Control Computers, or “Supernodes,” across RS-422 buses. A custom simple serial protocol ensures bus contention issues are avoided. The Supernodes are general-purpose attitude control computers based on the Motorola DSP 56303 processor (see Figure 7). One Supernode is in charge of managing data from all sensors, including sun sensors, magnetometers, rate sensors, and the star sensor. It also sends commands to the actuators, namely the reaction wheels and magnetorquers. Only one Supernode is on at any given time, while the other is left as a spare for backup operations if necessary. The functioning Supernode also runs the tightly timed control software on the satellite. The control law, extended Kalman filtering, ephemeris, orbit, and magnetic field models all run on this processor. It is also in charge of executing the attitude control modes of the satellite. It routes data to other processors like the CCD Drive Computers and the microcontrollers in the reaction wheels, and also watches for fault conditions necessitating the closure of the telescope lens cap to protect the instrument. The ACS Supernode is comprised of two parts: a standard compute core, and an application specific nodule that can be

tailored to the needs of a particular mission. A complete list of features is shown in Tables 2 and 3. Like other custom boards, the Supernodes monitor and report their own health, and the health of the actuators and sensors under their control.



**Figure 7: Attitude Control Computer or “Supernode”**

The multipurpose ACS Supernode can be tailored to interface with and process data from commercial off-the-shelf sun sensors and magnetometers. It also has the

ability to drive up to three independent magnetorquers for magnetically based pointing control. Several serial communication ports allow networking with other on-board computers (telemetry and command channels) while also allowing the direct control of Dynacon's miniature reaction wheels.

**Table 2: ACS Computer – 1/bis Compute Core**

Processor	<ul style="list-style-type: none"> <li>Motorola DSP56303</li> <li>24-bit integer/fixed-point DSP</li> </ul>
Clock Speed	<ul style="list-style-type: none"> <li>Software configurable by PLL</li> <li>Up to 80 MHz</li> </ul>
RAM	<ul style="list-style-type: none"> <li>512 k x 24 bit SRAM, 15 ns access speed</li> <li>3 k x 48 bit on-chip data RAM, zero wait state access</li> <li>1 k x 24 bit on-chip program RAM, zero wait state access</li> <li>Software EDAC</li> </ul>
Cache	<ul style="list-style-type: none"> <li>1 k x 24 bit instruction cache</li> </ul>
ROM	<ul style="list-style-type: none"> <li>32 k x 8 bit EPROM containing bootloader</li> </ul>
Mass Storage	<ul style="list-style-type: none"> <li>16 M x 8 bit sequential access flash storage</li> <li>Software EDAC</li> <li>Write protect feature disables charge pumps when not needed</li> </ul>
Interfaces	<ul style="list-style-type: none"> <li>4 asynchronous serial ports, with transmit enable control</li> <li>2 synchronous serial ports, with independent transmit and receive clocks</li> <li>1 SPI interface</li> <li>24 digital input/output lines</li> <li>Reset, NMI, and peripheral interrupt</li> <li>PWM/event timer</li> </ul>
Built-in Test	<ul style="list-style-type: none"> <li>Embedded temperature sensor (read by application board)</li> </ul>
Power	<ul style="list-style-type: none"> <li>Requires external +3.3 V, 300 mA supply</li> </ul>
Footprint	<ul style="list-style-type: none"> <li>Fits within 100 mm x 160 mm envelope</li> <li>Plugs into application board</li> </ul>
Connectors	<ul style="list-style-type: none"> <li>Two 40 conductor flex cables connect to application board</li> </ul>

Powerful instrument drive electronics based on the latest digital signal processors are available to collect science data with timing accuracies in the millisecond range and timing precision in the microsecond range (see Figure 8).

The CCD drive electronics for MOST must acquire, process and store continuous streams of photometric data, while protecting that data from radiation upsets using Error Detection And Correction (EDAC) software. These electronics also serve to generate precise attitude error estimates using highly optimized star tracker routines. The MOST instrument electronics and software enable processing and memory intensive science and attitude determination functions to be performed with unparalleled ease.

Custom software drivers allow instrument electronics to communicate efficiently with other computers on board the satellite. Additional computers may be added without significant increases in software or operating complexity.

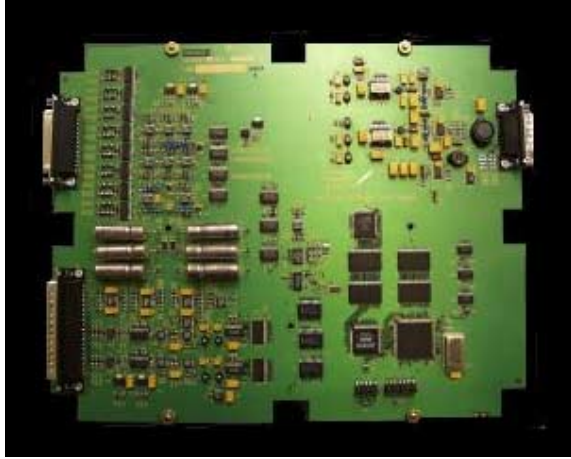
**Table 3: ACS Computer – Application Board**

Line Drivers	<ul style="list-style-type: none"> <li>Two 4-wire full-duplex RS-485 ports</li> <li>Two 2-wire half-duplex RS-485 ports</li> </ul>
Analog Inputs	<ul style="list-style-type: none"> <li>Thirteen 12-bit analog inputs with configurable input networks</li> <li>Glueless interface to: <ul style="list-style-type: none"> <li>Four-quadrant photodiode sun sensors</li> <li>AD590 temperature sensors</li> <li>Potentiometer position sensors</li> <li>Ground referenced currents (positive only)</li> <li>Ground referenced voltages (positive only)</li> </ul> </li> <li>Internal one-pole anti-alias filter, can be set to any desired time constant</li> </ul>
Power Outputs	<ul style="list-style-type: none"> <li>Four power outputs</li> <li>Each line factory configured to ground OR FET switched +5 V</li> <li>Use to power sun sensors, Billingsley magnetometers, AD590 temperature sensors, or other equipment</li> <li>Switched lines allow equipment to be turned off when not needed</li> </ul>
Digital Inputs	<ul style="list-style-type: none"> <li>Four digital inputs</li> <li>LVTTL logic levels</li> <li>Each line factory configured with resistor or short to ground or +3.3 V</li> <li>Pull-ups allow interface to open-collector gates</li> <li>Optional shorts allow use as ground or +3.3 V power output lines</li> </ul>
Digital Outputs	<ul style="list-style-type: none"> <li>3 digital outputs</li> <li>LVTTL logic level</li> <li>High impedance on bootup</li> </ul>
Magnetometer	<ul style="list-style-type: none"> <li>Three channels</li> <li>0 to 5 V input range</li> <li>Independent two-pole anti-alias filter on each channel</li> <li>12-bit ADC resolution</li> </ul>
Magnetorquer	<ul style="list-style-type: none"> <li>Three magnetorquer interfaces</li> <li>Hardware current control loop</li> <li>No discontinuity through zero current</li> <li>Switch-mode supply for &gt; 90% efficiency</li> <li>12-bit DAC current command resolution</li> <li>Torquer circuit high impedance when off or upon software command, to permit redundant torquer windings driven by a second board</li> </ul>
External Interrupt	<ul style="list-style-type: none"> <li>RS-422 physical layer</li> <li>Drives core NMI line</li> </ul>
Built-in Test	<ul style="list-style-type: none"> <li>Board temperature</li> <li>Digitization of core temperature</li> <li>+3.3 V current</li> <li>+5 V current</li> <li>Magnetorquer current control test</li> </ul>
DC/DC Converter	<ul style="list-style-type: none"> <li>Requires 6 – 35 V supply</li> <li>Provides +3.3 V for core</li> <li>Provides clean +5 V for peripherals and external devices</li> </ul>
Footprint	<ul style="list-style-type: none"> <li>100 mm x 160 mm 3 U Eurocard</li> <li>Core board bolts on top, or on side</li> </ul>
Connectors	<ul style="list-style-type: none"> <li>2 40 conductor flex cables connect to core board</li> <li>Single 50-pin DSUB connects to spacecraft</li> <li>Eurocard rectangular connector is not installed</li> </ul>

The MOST instrument electronics communicate with the ACS Supernodes that run intense attitude determination and control algorithms based on collected sensor data and



actuator availability. Precise timing is required to achieve the stringent pointing objectives of the MOST mission (better than half an arcminute pointing accuracy and stability).



**Figure 8: Instrument Drive Computer**

The CCD Drive Computers are instrument computers responsible for gathering science data and providing star sensing measurements to the ACS Supernodes. They are connected to the Supernodes via RS-422 buses using the custom simple serial protocol developed by UTIAS/SFL.

**Table 4: Instrument Computer Features**

General	The CCD Digital Signal Processor (CCD-DSP) board provides clocking signals, two signal-processing chains and one high speed DSP to process images from an EEV CCD47-20 CCD.
Principal Features	<ul style="list-style-type: none"> <li>• All clock and bias voltages independently controlled.</li> <li>• Two separate integrating signal processing chains with 14-bit analog-to-digital converters and programmable-gain amplifiers.</li> <li>• Motorola 56303 DSP controls clocking signals and signal processing chains.</li> <li>• Ovenized oscillator (7 ppm) controls DSP clock frequency for ultra-precise timing.</li> <li>• On-board switching power supply (8-15V) with linear regulators to provide quiet power to analog circuitry.</li> <li>• A 64Kx8 boot ROM and two banks of 512Kx24 fast SRAM protected from bit errors by an Error Detection and Correction (EDAC) system.</li> <li>• Two RS-422 communications channels.</li> <li>• On-board analog-to-digital converter for measuring board temperature and various power supply voltages and currents.</li> </ul>

One CCD Drive Computer is in charge of science data readout, processing, and managing the tight timing requirements between processing and taking images. The computer is responsible for clocking the Science CCD and setting the length of exposures. CCD temperature

control is also managed by this computer. The requirements of high-precision photometry require very low noise levels (down to 1-2 bits RMS out of 14-bit wide channels). These requirements are met by providing a very carefully designed power system, grounding and shielding strategy. The CCD Drive Computer is ideally suited to manage instruments requiring very low noise in the measurement signal chains. The second computer is used to collect star field images for precise attitude determination. Using highly optimized software developed by Dynacon Enterprises Limited, star field images are correlated against local star maps for precise attitude error sensing under strict timing requirements. Both CCD Drive Computers regulate the temperatures of their respective CCDs, and report telemetry from the instrument and the electronics. A list of technical features is given in Table 4.

### *Telemetry and Command*

Contact with the ground is established using high efficiency receivers and transmitters designed and developed by the UTIAS Space Flight Laboratory in collaboration with the Electrical and Computer Engineering Department of the University of Toronto. Transmitter efficiencies upwards of 30% are possible for missions where available power is at a premium. Switchable uplink and downlink rates, and the use of standard Amateur Radio protocols allow the inexpensive operation of the satellite using affordable ground stations that can be controlled from locations defined by the scientist. Easy-to-use terminal programs allow seamless communications with the satellite payload, as if the scientist's computer were directed connected to the instrument.



**Figure 9: Telemetry and Command Smartnode**

The communications subsystem for MOST consists of telemetry and command "Smartnodes", receivers, transmitters and antennas. The Smartnodes (Figure 9), developed by UTIAS/SFL, provide the modem interface to the receivers and transmitters. Variable modem speeds

are commandable from the ground and various modulation schemes may be adopted. The scheme chosen for MOST is Gaussian Minimum Shift Keying (GMSK), but others are possible.

The Smartnodes also provide telemetry collection and conditioning services to the rest of the satellite. “Firecode” ROMs provide emergency and/or immediate control of key satellite features, and sense special bit sequences sent from the ground which instantaneously get translated into the appropriate actions on the satellite.

**Table 5: Telemetry & Command Smartnode Features**

Telemetry	<ul style="list-style-type: none"> <li>Twenty four 12-bit analog inputs (0-5V) connected to a Serial Peripheral Interface (SPI) analog-to-digital converter (LTC1286) controlled by a 4-wire interface.</li> <li>Five of the analog inputs are configurable to read the output from AD590 temperature sensors. AD590 bias voltages available on main connector.</li> </ul>
Radio	<ul style="list-style-type: none"> <li>Scrambler/descrambler circuit implementing G3RUH algorithm (<math>x17+x12+1</math>).</li> <li>Two 64-bit firecode decoder state machines.</li> <li>Two CMX89A GMSK-based modems capable of speeds of up to 200 kbits/s for completely separate uplink and downlink bit rates.</li> </ul>
General	<ul style="list-style-type: none"> <li>All digital inputs and outputs from the board use RS-422 physical layer for noise immunity.</li> <li>On-board, highly efficient switching power supply (input voltage from 8-15VDC).</li> </ul>

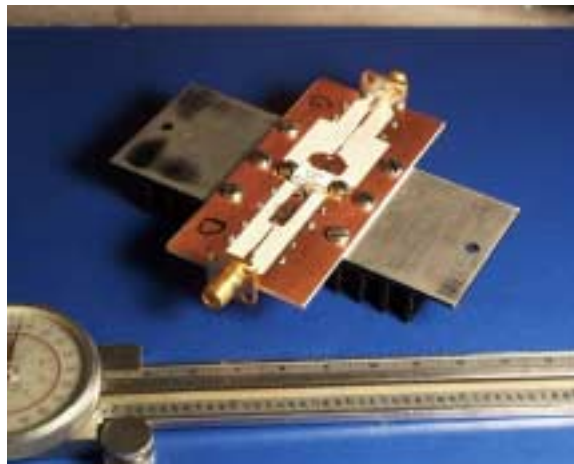


**Figure 10: Receiver Synthesizer**

The Telemetry and Command Smartnode has two principal sections. The first section gathers 24 channels of analog telemetry and the second acts as a modem. See Table 5 for a list of features.

The S-band receivers are highly optimized, low-power devices, designed using a superheterodyne approach. Each receiver on MOST draws 640mW of power and is

tuned for sensitivity and selectivity. Both the receiver and transmitter run off the same local oscillator for S-band conversion. Figure 10 shows a receiver synthesizer built for MOST.



**Figure 11: Transmitter High-Power Amplifier**

The S-band transmitters boast 30% efficiency at 10W (power in), and are controlled through a redundant switching scheme. The high power amplifier has an efficiency of 50%. The transmitter high-power amplifier is shown in Figure 11.

### *Attitude Control*

The MOST attitude control system is unusual for a microsatellite, requiring highly-accurate three-axis inertially-fixed stabilization, far better than can be achieved using the gravity-gradient boom stabilization approach typical of many past microsatellites. Dynacon is providing the MOST Attitude Control System, based on its miniature reaction wheel (called “MicroWheel”) and High Performance Attitude Control (HPAC) products. MOST’s HPAC capability will enable it to be one of the first *operational* space science microsatellites.

From Dynacon, a complete attitude control software suite is available. The hardware elements of the HPAC System include the ACS Supernode (available from Dynacon and UTIAS/SFL) and Dynacon’s MicroWheels. Dynacon’s MicroWheels have on-board processing and rate sensing. They may be operated in various modes, and the electronics can be tailored to speak the required communications protocol including CAN and UTIAS/SFL’s RS-422 Simple Serial Protocol. The reaction wheels, together with the ACS Supernode and software, are being used by other programs such as CHIPSat (SpaceDev and University of California at Berkeley), and FEDSat.



**Table 6: MicroWheel Specifications**

Size	102 x 94 x 89 mm
Mass	0.9 to 1.2 kg (configurable via rotor size)
Speed Range	+/-9000 RPM (nominal speed: 5000 RPM)
Ang. Momentum Capacity	0.05 to 0.25 Nms (configurable via rotor size)
Torque Capacity	30 mN-m
Data Interface	RS-232/422/485 (CAN bus optional)
Power Requirements	<ul style="list-style-type: none"> <li>0 RPM: 0.6W</li> <li>5000 RPM: &lt; 2.1W</li> <li>9000 RPM: &lt; 3.2W</li> <li>+ 1W for optional rate sensor</li> </ul>
Voltage	One unregulated power line 8-35V, plus a ground line.
Temperature Range	-20/+60C (operating), -40C/+70C (storage)
Speed Control Performance	< +/- 0.2 RPM (above 100 RPM)
Torque Control Performance	< +/- 1 mNm
Rate Sensor Performance	range from 50 to 500 deg/sec, drift rate ~ 5 deg/hour
Commands	speed or torque set-points, > 10 Hz command rate achievable
Telemetry	wheel speed, acceleration, torque, angular rate, pressure, temperatures, voltages
Design Life	5 years

**Table 7: HPAC System Library**

<b>Module</b>	<b>Description</b>
Mode Executive	Sequences the implementation of the ACS control modules so that the correct ACS mode is implemented
Detumble	Implements a B-dot control law
Ephemeris	Solar – Earth/Sun vector Orbit – satellite position Lunar – geocentric Moon position
ACS Timing	Coordinates ACS timing
Magnetic Field Model	Expected Earth magnetic field vector at satellite location
Wide-Field Sun Sensor	Coarse satellite/sun vector
Desaturation	Use magnetorquers to desaturate wheels
Reference Motion Generator	Produces a trajectory of orientations that will take the spacecraft from the initial orientation to the target orientation
Attitude Estimation	Merges sensor measurements to estimate orientation
Inertial Attitude Control	Produces reaction wheel torque commands that provide all pointing control torques
Reaction Wheel Drive	Interface between ACS Supernode and reaction wheels
Magnetorquer Drive	Takes input magnetorquer magnetic dipole commands and converts them to magnetorquer current commands
Sensor Drivers	Sun Sensor – h/w interface Lunar Sensor – h/w interface Magnetometer – h/w interface
T&C General Interface Driver	Provides for collection of telemetry from all software modules

The MicroWheel (Figure 12) is a "smart" sensor/actuator pair. It includes both a *reaction wheel*, and a *solid-state angular rate sensor*, both of which are operated locally by an embedded *micro-controller*. The rotor dimensions

are specified by the customer, to allow angular momentum and mass to be traded. The micro-controller implements local speed and torque control loops for the reaction wheel, allowing the reaction wheel to accurately track speed or torque commands from a satellite's attitude control computer. Commands and telemetry (measured wheel speed, acceleration, torque, rate sensor reading, temperatures, voltages and internal pressure) are communicated via a serial interface. See Table 6 for a complete list of MicroWheel specifications.

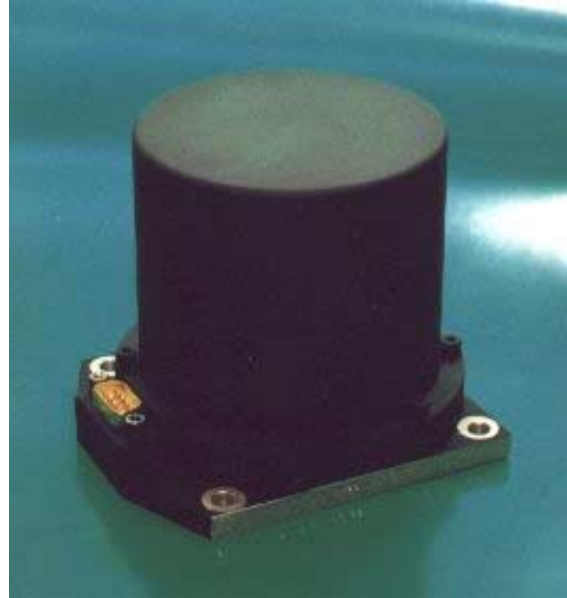
**Figure 12: Dynacon's Miniature Reaction Wheel**

Table 7 summarizes the features of Dynacon's High Performance Attitude Control System Library. The library consists of a number of modules that can be used to tailor the attitude control system to the needs of the particular microsatellite mission of interest. These modules run on the ACS Supernode (Figure 7).

## Conclusion

### *Adapting the MOST Microsatellite and Ground Stations for Other Missions*

The various components of MOST represent modular technologies that may be modified and rearranged to suit a wide range of microspace missions. The modular on-board computer components show versatility in the manner in which they may be connected and used. Different instruments and different attitude control approaches can be accommodated with this powerful set of computing equipment. The high performance receivers and transmitters may be used on any microsatellite mission, and the modulation scheme, data

rate, and communications protocol may be modified to suit specific needs. The high-performance attitude control system can be tailored to suit the needs of any scientific objective. After achieving such high precision, three-axis pointing requirements as demanded by MOST, the door has been opened to the most ambitious missions, and the full range of attitude control possibilities – from gravity gradient and magnetic control to inertially fixed pointing – are within reach. Inexpensive ground stations may be established quickly at any desired location and may be controlled remotely using virtual links to on-board satellite payloads and equipment. The MOST mission has clearly created a continuing means to provide low-cost access to space for the ambitious science and technology missions of tomorrow.

### *Canadian Expertise and Facilities Available for Future Missions*

As a result of the MOST mission, the Dynacon-UTIAS/SFL team has developed expertise in thermal modeling and control, having dealt with the challenging thermal problems associated with a three-axis stabilized microsatellite. The team has also become expert at designing light yet strong structures for microsatellites that allow easy integration and de-integration, thereby reducing costs during the assembly, integration and test phase of satellite development. Efficient power systems have been designed that may be used in future missions as well, optimized with thermal considerations in mind. An elegant balance is achieved between power generation, efficiency, and thermal control.

The MOST mission has enriched the Space Flight Laboratory, a unique lab in Canada involved in low-cost space projects and microsatellite missions, and Dynacon Enterprises' Microsatellite Systems Division, expert in systems engineering, quality assurance, attitude control, and power systems. Facilities have been installed that enable the design and development of inexpensive but highly effective satellites and their subsystems. Special technologies have been developed based on proven techniques, such as powerful on-board computers using fast digital signal processors and efficiency optimized radios for microwave communications. In addition, a staff of engineers trained by AMSAT stands ready to meet the challenges of tomorrow's demand for low-cost access to space. As a university lab collaborating with Dynacon, Canada's leading enterprise in low-cost space systems solutions, the Space Flight Laboratory is able to draw upon funding from both the public and private sectors. Both Dynacon and UTIAS/SFL encourage scientists and engineers to join them in defining collaborative space projects of mutual interest.

### **Acknowledgments**

The authors would like to thank Jaymie Matthews, the Principal Investigator and Rainer Kuschig, the Instrument Scientist at UBC for their contribution to the smooth execution of the MOST program. Because of the flexibility of the science team and the capability of the instrument designers, we are able to deliver more science performance than initially contracted while staying within the program's budget and schedule parameters.

Dynacon Enterprises Limited gratefully acknowledges the support of the Canadian Space Agency, Space Science Branch. The UTIAS Space Flight Laboratory would like to acknowledge the support of Dynacon Enterprises Limited, the Ontario Research and Development Challenge Fund, the Center for Research in Earth and Space Technologies (CRESTech), the University of Toronto, and the Natural Sciences and Engineering Research Council (NSERC) for financially supporting the MOST project and the installation of lab facilities.

The authors would also like to acknowledge the following sponsors who have donated software or equipment to UTIAS/SFL, and who's generosity has helped to create a world-class university microsatellite laboratory:

Analytical Graphics Incorporated  
Agilent Technologies  
Structural Dynamics Research Corp (SDRC)  
Integrated Systems Incorporated  
Autodesk  
National Instruments  
Cadence  
Raymond RMC  
Micrografx  
Tasking Incorporated  
Altera  
ATI Technologies  
ENCAD  
Rogers Microwave Materials Division  
JDL Productions

### **References**

- [1] Carroll, K.A., Zee, R.E., Matthews, J. "The MOST Microsatellite Mission: Canada's First Space Telescope." 12<sup>th</sup> Annual USU/AIAA Conference on Small Satellites, Logan Utah, 1998.