

CHIPS: A NASA UNIVERSITY EXPLORER ASTRONOMY MISSION

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Abstract. On January 12th, 2003, the Cosmic Hot Interstellar Plasma Spectrometer Spacecraft (CHIPSat) launched successfully from Vandenberg Air Force Base as a secondary payload on a Delta II booster. CHIPSat completed commissioning in February 2003, and is now a fully operational observatory. The main science objective is to measure extreme ultraviolet emissions from the interstellar medium. Data on the distribution and intensity of these emissions allow scientists to test competing theories on the formation of hot interstellar gas clouds surrounding our solar system. CHIPSat is the first satellite in NASA's University-class Explorers Program (UNEX) to make it to orbit. The UNEX program was conceived by NASA as a new class of explorer mission charged with demonstrating that significant science and/or technology experiments can be performed with small satellites, constrained budgets and limited schedules. This paper presents the CHIPSat design, discusses the on-orbit performance to date, and provides lessons learned throughout the project.

Introduction

The Cosmic Hot Interstellar Plasma Spectrometer spacecraft (CHIPSat), the first of NASA's streamlined University-Class Explorer missions, was launched out of Vandenberg Air Force Base (VAFB), CA on January 12th, 2003. CHIPSat is a small 64 kg spacecraft carrying a single extreme ultraviolet (EUV) spectrograph. The spectrograph, in its 600 km polar orbit, measures the intensity and distribution of EUV glow at wavelengths of 90 to 260 Å. CHIPS data provides information on the electron temperature, ionization conditions, and cooling mechanisms of the hot plasma contained in the interstellar medium. The hot million-degree plasma is believed to fill the part of space where our solar system is situated known as the 'local bubble'. By testing competing models, CHIPS will provide important clues about the formation and evolution of galaxies.

The baseline CHIPS mission is one year. The initial campaign has been spent observing

regions of particular interest long enough to provide the signal to noise ratio (S/N) detection required for the strongest emission lines. Many of these regions, at the galactic pole, have been observed to a depth of about 300,000 seconds per resolution element (resel). Each resel is 5° x 25°. CHIPS initial science results were presented at the AAS High Energy Astrophysics Division meeting in March 2003.

CHIPS Instrument

The CHIPS instrument, developed at the Space Sciences Lab at UC-Berkeley (UCB), is a multi-channel spectrograph. Science requirements called for a $\geq \lambda/100$ (Rayleigh's criterion) survey across the 90-260Å bandpass. The design baselined to meet those requirements consisted of six spectrograph channels directing light on to a single focal plane. The focal plane is a photon-counting microchannel plate detector. (See Figure 1).

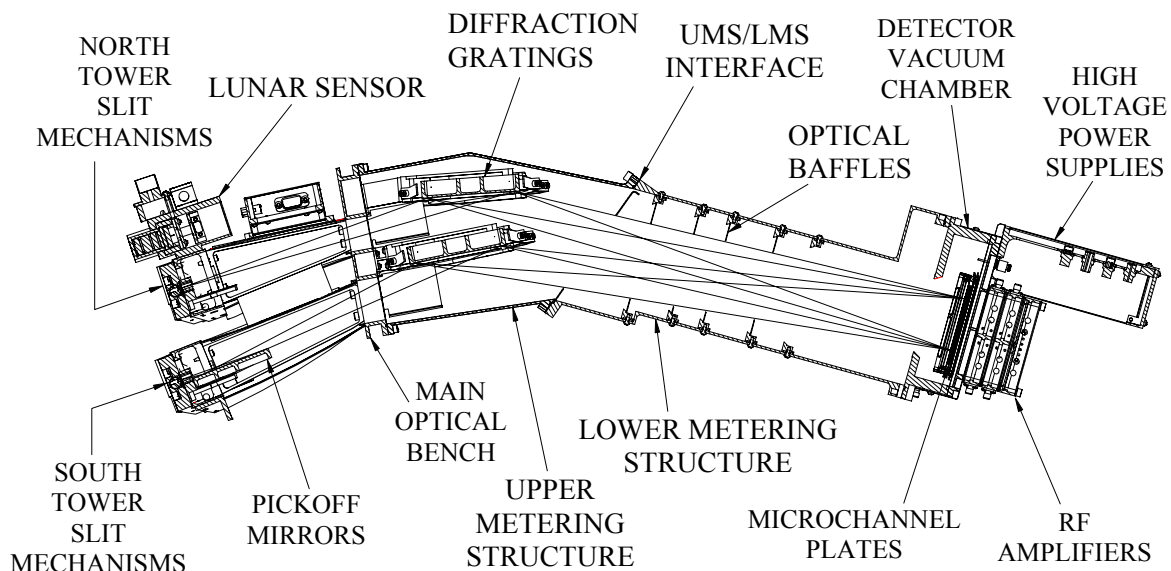


Figure 1: CHIPS Baseline design. Six optical channels deliver light to a single MCP detector. The spectrometer and microsatellite were designed to fit in the 30cm envelope between the Delta-II avionics section and outer skin.

Slit Mechanisms Design and On-Orbit Performance

Light enters the spectrograph channels through six slit mechanisms, each with a wide (1000 μm) or narrow (250 μm) photoetched beryllium-copper slit. Slits are separated by $\sim 1\text{mm}$.

Operators command the slits to wide, narrow, or closed, setting the position of a cover wheel to block light to either or both slits. The slit wheel is powered by a beryllium-copper rotary spring, and motion is affected via a shape memory alloy ratchet/pawl mechanism. (See Figure 2).

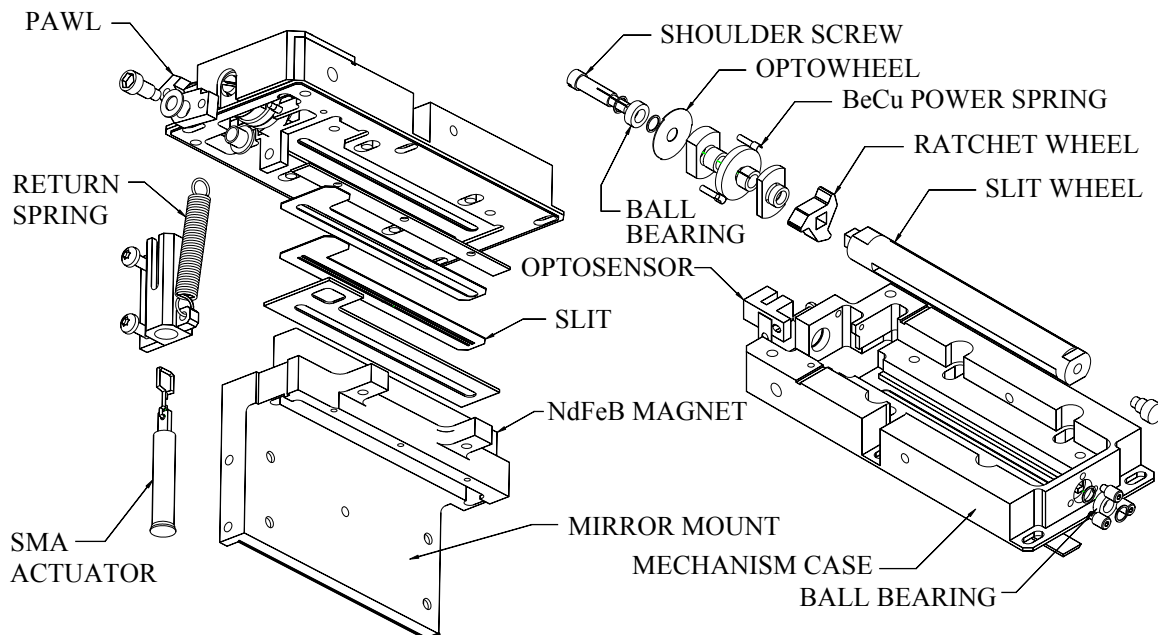


Figure 2: Slit Mechanism. Slit wheels are powered by BeCu power springs, and initiated by a 2-stage nitinol actuated ratchet/pawl assembly. The wheel has channels, which allows light to pass through the wide, narrow or neither slit.

The slit mechanisms were closed throughout final integration and on launch to protect the optics from contamination. During instrument commissioning on-orbit, all slits were commanded to the wide position. Sky survey data was taken for approximately a month in this configuration to identify possible regions of interest. The slits were then commanded to narrow for finer resolution data. All slit mechanisms have performed without incident on-orbit.

Diffraction Grating Design and On-Orbit Performance

Light passing through the entrance slits illuminates individual, identical diffraction gratings. Gratings are of cylindrical figure, with varied line-spacing to eliminate cylindrical aberration. Substrates are open-backed Zerodur, and held in a semi-kinematic mount by three beryllium-copper flexures. The diffraction gratings were aligned to a handful of arcseconds,

and all six channels were coaligned within 0.1\AA . In order to keep project costs down, a cantilevered optical design was employed, with a traditional milled aluminum metering structure. (The metering structure is a thin non-planar shell, designed to fit between the avionics section and outer skin of the Delta-II, and manufactured entirely on a 3-axis milling machine.) Tangential flexure blades allow for the rather-large coefficient of thermal expansion difference between the Zerodur gratings, and the aluminum optical bench. Zerodur is clamped with a constrained-displacement viton joint, and adjustment motion is allowed via oversized clearance holes in the blade bases. No adhesives, or invar, were used in the optics mount. (See Figure 3). From periodic lunar calibrations on-orbit, it has been verified that the gratings maintained co-alignment during launch. In addition, thermal degradation of alignment or spot position has not been observed.

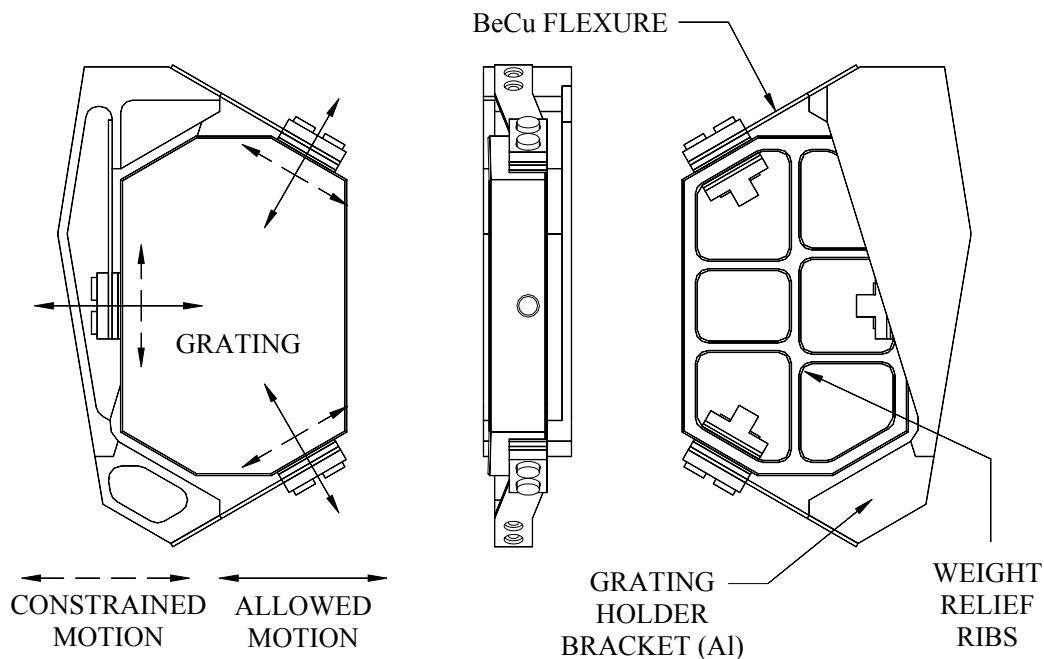


Figure 3: Grating mount design. Semi-kinematic principles were implemented. Flexures constrain motion tangential to the geometric center of the grating (including motion out of the page), while allowing motion toward the grating center. This specified a location for the grating, while inducing minimal mount thermal stress in the Zerodur substrate.

MCP Detector Design and On-Orbit Performance

The gratings disperse and focus the diffuse extreme ultraviolet radiation onto a single focal plane through a filter assembly. Photons are collected by a large (60mm active diameter) crossed delay line (XDL) microchannel plate (MCP) detector. The multi-layer XDL anode, uses isolated cross fingers and external delay lines for X and Y to provide photon position. The anode has a 69mm active area with delay lines to the side providing a $\sim 1.2\text{nS/mm}$ delay, 0.6mm period. The MCPs are made of a high resistance glass, treated with a deposit of NaBr, 6000A to 9000A, applied at an incidence angle approximately 5 degrees to pore axis. They are approximately 75mm in diameter with a 65mm active area.

Thin metal filters are clamped $\sim 1\text{cm}$ above the MCPs, and used to filter unwanted background radiation. Poly/B, Aluminum, and Zirconium filters are used to maximize the CHIPS bandpass (90A to 260A), maximize the bandpass sensitivity, and reduce geocoronal noise.

To operate, the detector requires high voltage at approximately $\sim 5000\text{V}$. The high-voltage system was designed to be low-risk, with ORFEUS-heritage redundant high voltage power supplies (HVPS) from Spacom. HV cables and connectors were not employed in the design. Instead, removable HVPSs were installed directly to the detector chassis via a vacuum feedthrough. No on-orbit anomalies have been encountered with the high voltage system.

The detector was kept at vacuum through spacecraft and launch vehicle integration in order to preserve MCP performance, and prevent acoustic damage to the thin metal filters. During instrument commissioning on-orbit, the vacuum box door was commanded open, actuating a one-

shot shape memory alloy actuator to a release door mechanism.

The CHIPS detector is performing very well on orbit, with a uniform, low background rate of 20-25cps (counts per second) and no 'hot spots'.

Instrument Electrical System Design and On-Orbit Performance

Figure 4 provides a block diagram of the CHIPS electrical system and principle interfaces. The photon-counting system converts light focused on the spectrometer's photosensitive front surface into a stream of digitized photon coordinates. In-band photon locations are determined using a XDL anode, converting the light into analog electronic pulses. RF amps amplify the anode signal and the pulses are converted into digitized coordinates by a Time to Digital Converter (TDC) in the Instrument Electronics Box (EBOX). The digitized events are transmitted to a Data Processing and Housekeeping Unit (DPU/HK) for processing. The DPU/HK board packages and formats all instrument data for transmission to the CHIPSat Single Board Computer (SBC) via redundant asynchronous RS-422 links. Science and instrument housekeeping data is then stored within spacecraft memory and combined with orientation data before downlink.

Low-current power to the instrument Low Voltage Power Supply (LVPS) and high-current power to the instrument door and cover actuators is supplied directly from the spacecraft 14V batteries (through the spacecraft unregulated power supply). The LVPS incorporates its own power converters to generate the required secondary voltages. The spacecraft provides switched heaters to keep the instrument within its survival temperature range.

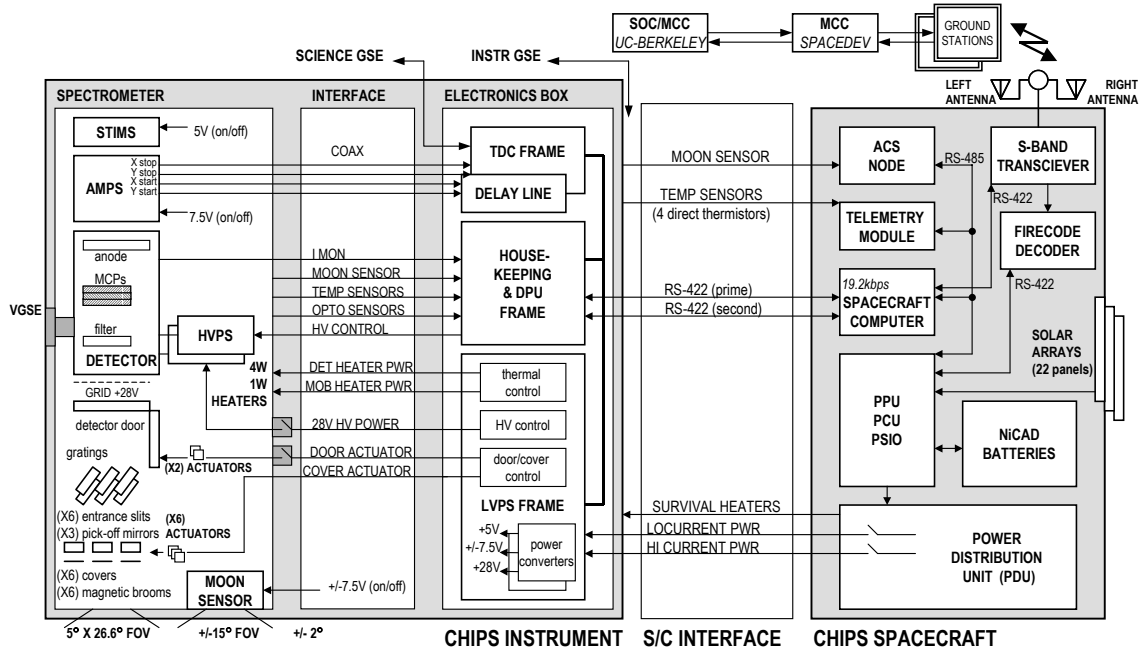


Figure 4: CHIPS Electrical System Block Diagram.

Time to Digital Converter (TDC)

The TDC is responsible for processing valid photon events (converting analog pulses from the RF amps to digital detector X, Y coordinates and charge amplitudes) and rejecting sub-threshold or incomplete events. It is comprised of three main sections and their associated interface circuitry: (1) a front end, consisting of four constant fraction discriminators (CFDs) and four charge-to-amplitude converters (QACs), one each for the X-Start, X-Stop, Y-Start, Y-Stop input amplifier signals; (2) a pair of time-to-amplitude converters (TACs), one for each X, Y channel; and (3) the analog-to-digital conversion (ADC) and output interface circuitry.

Data Processing and Housekeeping (DPU/HK)

The DPU/HK is responsible for packaging and formatting science data from the TDC and instrument health and status data. Data is formatted into 8-bit words for transmission to Spacecraft Single Board Computer (SBC) via redundant RS-422 asynchronous serial links. The DPU/HK is also responsible for commanding all instrument power switching and distribution (door/cover actuator control, detector high voltage control, thermal control, and moon sensor control). The design

architecture is centered on a Rad-tolerant 8051 processor (UT69RT051) and Actel 1020 FPGA (RT 1020-CQ84B) and includes 64K PROM and 512K RAM. The board incorporates 40 analog monitoring signals for current and voltage monitors, temperature monitors, moon sensor data, HVPS monitors, door position monitors, and cover position monitors. 32 bi-level signals power on or off instrument heaters, door and cover actuators, HVPS units, amps and stim-pulser, and monitor associated read backs.

The DPU/HK software monitors the state of the MCP high voltage power supplies. There is a commandable current threshold which powers off the HVPS if a limit is exceeded. This has not triggered on orbit. There is also a count rate monitoring mechanism that automatically ramps the high voltage down when counts exceed a hardware threshold. This mechanism routinely triggers on orbit, during passages through the South Atlantic Anomaly and the Northern and Southern Outer Magnetic Belts. Figure 5 illustrates the instrument count rates and shows a rate shutdown event associated with a passage through the Northern Outer Magnetic Belt. The subsequent passage through the belt was not

severe enough to trigger the shutdown mechanism.

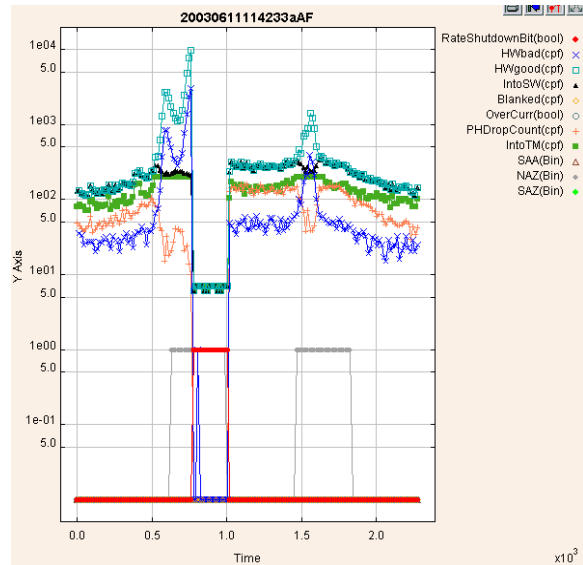


Figure 5: HVPS autonomous shutdown on orbit.

Low Voltage Power Supply (LVPS)

The LVPS provides regulated +/- 7.5V, +5V and +28V to instrument subsystems, converted from an unregulated +14V provided by the spacecraft. The design incorporates Linear Technology Switching Regulators and CUK and BUCK Converter topologies with overall efficiency ranging from 85% to 70% at nominal loads. All services are current limited and individually

voltage and current monitored. EMI is reduced with individual shielding of each service.

CHIPS Spacecraft

The CHIPS Spacecraft (CHIPSat) bus, developed SpaceDev Inc, is a 3-axis stabilized spacecraft using 4 momentum wheels, 3 torque coils, sun sensors, a magnetometer, and rate sensors to provide ~2 degrees attitude knowledge and control. Dynacon Inc provided the ACS subsystem. The 3-axis configuration not only provides the ability to accomplish a full sky survey of the entire celestial sphere, but also allows for very deep observations of regions of particular interest.

The mass for the entire satellite inclusive of the instrument is less than 64 kg. Dual-junction GaAs/InP/Ge body-mounted solar arrays with Nickel Fiber Cadmium batteries provide the necessary 40W of power. The primary solar arrays are body mounted on three sides of the spacecraft with small keep-alive arrays positioned on the other sides providing enough power to run critical subsystems regardless of the spacecraft's attitude. (See Figure 6).

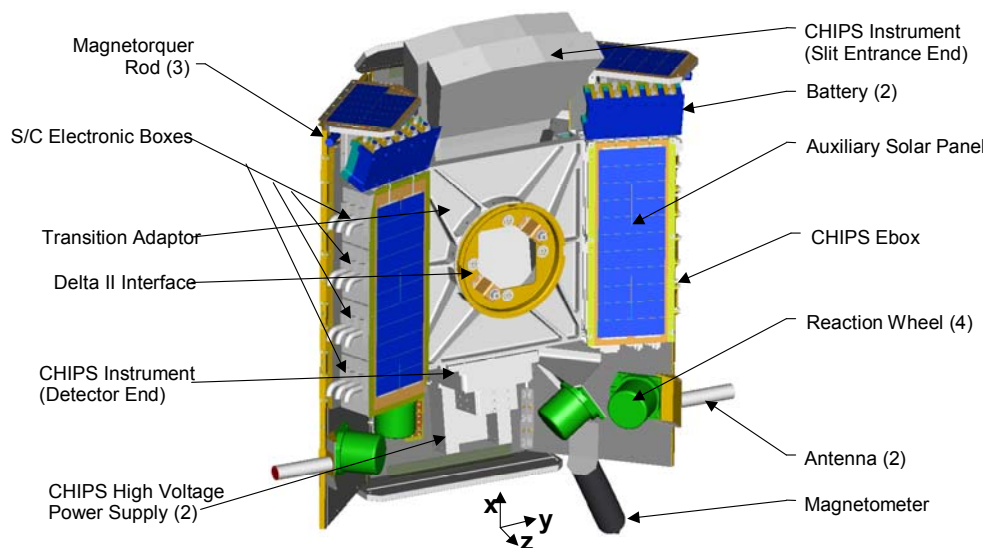


Figure 6: CHIPSat Rendering.

Signals from the instrument and spacecraft subsystems are acquired, formatted and stored by the spacecraft's data handling system, a single-board flight computer running a Motorola PowerPC 750 CPU. CHIPSat uses a S-band transceiver for RF communications. A pair of canted turnstile antennas mounted on opposite sides of the spacecraft, with opposite circular polarizations, provides an omni-directional beam pattern.

Science and housekeeping data is stored within spacecraft memory and downlinked several times daily to S-band ground stations at UCB, NASA's Wallops Flight Facility (WFF), and Adelaide, Australia (ITR). Data is then routed to the Mission Control Center (MCC) co-located with the Science Operation Center (SOC) at UCB where it is monitored real-time and archived. The MCC was located at SpaceDev during the first four months of early operations, and then relocated to UCB for nominal operations.

Early Operations

CHIPSat was designed as a capable system with near-autonomous survivability. The design included margin and limited (strategic) redundancy while keeping within cost, weight, and operational constraints. One of the primary features of the system's on-orbit survivability is the ability to commission the bus without any time-critical events and with as much operator validation and verification as desired.

Safe-hold Mode

After separation from the launch vehicle, no matter how CHIPSat was ejected or subsequently disturbed by environmental torques, the spacecraft was designed to: acquire enough power to operate the necessary systems to communicate with the ground; close the ground link in any attitude or rotation; achieve thermal survivability (in case passive control predictions are in error); and maintain the payload in a safe configuration. In this mode (termed safe-hold mode), the essential bus and the flight computer are powered on at all times. However, the flight computer sleeps for a fixed duty cycle in order to save power. The transmitter is powered on at a duty cycle that is

determined by the current state of battery charge, in order to provide an "emergency-broadcast" of basic spacecraft housekeeping telemetry. This duty cycle may range from a minimum of 10% to a maximum of 100%, with a fixed period (nominally 10 minutes). Therefore, in safe-hold mode, only basic spacecraft housekeeping and communications functions are performed. CHIPSat has no attitude knowledge or control when in safe-hold mode. This behavior is possible due to auxiliary solar panels, ensuring the spacecraft is power-positive in any attitude or tumble condition.

Once the spacecraft has been commanded to nominal mode, two primary events can cause it to return to safe-hold mode -- a power critical situation and/or a flight computer fault. If the spacecraft battery is drained completely, the entire non-essential bus, including the flight computer, is powered off in a graceful degradation of spacecraft functionality via a hardware load-shed. Only the non-essential bus remains powered to provide battery charge control and allow direct ground control over the power system. Excepting operator override, this critical power mode is maintained until the battery has reached a capacity sufficient to maintain safe-hold power conditions. The flight computer is then powered on and the spacecraft enters safe-hold mode. Due to the sizing of the auxiliary solar panels, CHIPSat should never enter the critical power mode unless there is a problem with the battery charging system or multiple solar array circuits. The spacecraft will also enter safe-hold mode if the flight computer determines a significant fault in the system after the normal start-up sequence. Ground operators are then afforded the time to diagnose and fix the problem.

On-orbit Checkout

In the first days after launch, each spacecraft subsystem and its major components were checked out via the same individual commands used during the Integration and Test (I&T) phase. After this initial check-out period, the flight operations team commanded the spacecraft to "orient" itself (via autonomous closed-loop control), using the earth's magnetic field to reduce its rotation rate and begin

acquiring signals from the sun. This detumble process took 2-3 orbits (~200 minutes). Once detumbled, the spacecraft was ready to begin planned pointings to the specified accuracy. Using FTP-uplinked batch commanding, an operator uploads a pointing schedule using a sequence of spacecraft/payload timed-file commands or mission data loads that are stored in flash memory on the spacecraft's flight computer and kept in queue. These commands can be overridden by a higher priority individual command as necessary.

CHIPSat commissioning took approximately 10 days as the flight operations team cautiously checked out all elements of the satellite prior to commencing closed-loop operations. Since all spacecraft commands and mission operations hardware and software were identical during testing (especially during thermal vacuum testing) and on-orbit operations, the results of the actual on-orbit checkout were predictable and accepted with high confidence. In fact, within days of commissioning the bus, automated software was used within the Mission Control Center (MCC) to allow for automated data limit checking. An emergency paging function was also implemented to lessen the operations personnel requirements even further, allowing the transition to 5 day x 8 hour operations.

Nominal Operations

Important to nominal mission operations, all ground segment and software design features were implemented using end-to-end IP communication and the Internet. With access to a LAN, IP address, and a network of IP-communications compatible ground stations, this architecture allows for a virtual mission operations center with mission control software that is easily portable.

In addition, this architecture proved to significantly shorten the System-Level I&T Phase. Throughout the project, Internet protocols were used to support early "virtual integration" of components. This phased development of integration and testing allowed the CHIPS team to connect systems over the Internet, working out software and data interface problems prior to subsystem flight build, test and delivery.

A TCP/IP stack and existing utilities (such as FTP) built into a WindRiver VxWorks RTOS in the spacecraft single board computer (SBC) provided an essentially "Free" infrastructure for moving data between the core spacecraft system and the ground segment. At the SpaceDev Facility, the SBC was interfaced to telemetry and power control boards over a multidrop RS-485 serial bus, representing most of the core devices on the bus. Through the Internet, science data was obtained from the Instrument using the facilities at the Space Sciences Lab at UCB, virtually transferred through the spacecraft system at SpaceDev, and routed back to the Science Operations Center at UCB. Similar to this testing with the Instrument, the last device on the serial bus was the ACS control computer located at Dynacon, Inc in Canada. The ACS system was tested over the Internet using PC-based code that was eventually ported to VxWorks and embedded in the spacecraft.

Use of COTS Technologies

CHIPSat uses a mixture of heritage and custom-designed components. While the heritage components are primarily space-rated, many of the custom-designed components are centered around the use of COTS electronics piece parts. In order to qualify the COTS piece parts for use in the space environment, a thorough test program was employed throughout the development cycle of the CHIPSat bus. The qualification program consisted of a variety of tests at the component and system level, including: thermal stress screen; thermal cycle; thermal vacuum; vibration; shock; EMI/EMC; total-dose radiation; magnetics; and solar irradiance. The test program was used to verify the basic part quality of the COTS piece parts, their applicability to the space environment, and the workmanship of their construction and assembly into CHIPSat components.

The use of COTS interface technologies greatly simplified the design, build, and test of the CHIPSat bus. For internal communications within the bus, standard COTS interface protocols are used, most notably RS-422 and RS-485. The interface between the spacecraft and the ground segment consists of an HDLC point-to-point link layer. Layered within the HDLC frames is a

standard TCP/UDP/IP protocol stack that, when combined with VPN and firewall-protected use of the commercial Internet, allows end-to-end data flow between the Mission Control Center, Science Operations Center, and the spacecraft. Because TCP/IP is used for end-to-end communications, almost all hardware in the ground segment is COTS; in addition, almost all communications-related software is built into the COTS operating systems used for both the ground and space segments. The use of COTS hardware and software reduced the development work required for the CHIPSat communications system, increased the efficiency of ground testing, and simplifies on-orbit operations.

Electronics Design and On-Orbit Performance

One of the principal concerns with the use of COTS electronics in the space environment is the rate of SEE (Single-Event Effects). The CHIPSat bus was designed to include system-level protection against SEE's. During the first five months on-orbit, these design features have effectively minimized the effect of SEU's that have occurred. While SEU's in EDAC-protected memory have been seen, the sole area in which (presumed) SEE's have affected on-orbit performance has been in the bus onboard flight computer. During ground testing, only a single unplanned reset of the onboard computer was experienced (although extended duration tests were not performed routinely). However, on-orbit, the computer resets approximately once every three weeks. The resets do not seem to occur primarily within the SAA (South Atlantic Anomaly), and also do not seem to be coupled with periods of increased solar proton activity. This points to very-high-energy trapped protons or galactic cosmic rays as likely sources for the computer resets. The results of SEE testing on a prototype flight computer indicate that the upsets may be occurring in the processor's built in L1 cache, which is not protected via EDAC.

The application-level software running on the computer is designed to recover the spacecraft gracefully from such a reset. When the computer boots, it examines the spacecraft power and ACS systems; if these systems indicate that the spacecraft was operating nominally at the time of the reset, then nominal operations are resumed

without requiring operator intervention. After the first on-orbit reset, the software was modified so that the science observation schedule would be resumed automatically as well; therefore, science data collection resumes as soon as the computer resets. Using this technique, the resets that occur once every three weeks cause the loss of about 0.1% of possible science data.

Since the start of science data collection, the net duty cycle for the acquisition of valid science data is approximately 95%. This duty cycle represents only the efficiency of the CHIPSat bus in collecting and downloading science data, and does not include any measures of the quality of the data. The 5% data loss over the first five months of the mission was caused primarily by two losses of 3-axis control, and one unplanned load-shed of the CHIPS payload. Without these three incidents, two of which occurred during the first month of the mission, and the third of which was caused by a hardware anomaly with one of the onboard reaction wheels, the net collection duty cycle is approximately 99%.

In addition to the resets of the onboard computer that likely are caused by SEE's, some spurious values are detected periodically in the onboard bus data acquisition system. These spurs result in erroneous readings of voltages, currents, or temperatures onboard the bus, and occur once every couple of days. The source of these telemetry spurs is unknown, but they were seen throughout ground testing in addition to on-orbit.

On the ground, filtering software is employed that prevents the flagging of these telemetry spurs as dangerous conditions in order to minimize paging alerts that are sent automatically to the operations team.

The capability to reload all onboard software and algorithm parameters was used several times during the commissioning phase of the mission. Software upgrades have been performed for the spacecraft onboard flight computer, the ACS control computer, and the CHIPS payload computer. These upgrades have been used both to repair code bugs that surfaced on-orbit and to optimize both ACS performance and science data collection. Parameter upgrades have been used to

optimize ACS performance, and also to switch to the redundant reaction wheel when one of the primary wheels began to experience communications trouble on-orbit. All upgrades to software modules and parameter files are verified on the ground-based spacecraft simulator, or flatsat, prior to upload to the spacecraft. The use of the flatsat to verify onboard configuration upgrades is a key technique in reducing the risk associated with modifying the on-orbit spacecraft configuration.

ACS Design and On-Orbit Performance

Per the baseline science design, the CHIPSat Attitude Control System (ACS) is designed to accommodate the full-sky survey that is used to map the sky at the ultraviolet wavelengths of interest. For the baseline observation strategy, the spacecraft is pointed within 20 degrees of the sun during periods of orbital daylight. Because the boresight of the CHIPS telescope is mounted at right-angles to the main solar panels and medium sun sensor, this pointing constraint allows observations near the “terminator” plane. Because different sections of the terminator band are occulted by the Earth as the spacecraft moves along its orbital track, the CHIPS telescope must be pointed at two or three different targets per orbit. The 20-degree “terminator band” constraint maintains solar power generation within the levels budgeted during the mission design, and also ensures that the sun remains within the view of the 22.5-degree half-field-of-view medium sun sensor during orbital daylight, thereby maximizing ACS precision. In addition to the terminator constraint, the spacecraft pointing is restricted in order to prevent the CHIPS telescope from looking at the moon and Earth, and from looking in the ram direction.

Due to the terminator constraint, the full-sky survey mode takes six months to allow access to all parts of the celestial sphere while the spacecraft remains pointed at the sun during periods of orbital daylight. However, the sun-pointing constraint is relaxed during periods of orbital night. This technique allows CHIPS to point anywhere on the celestial sphere during orbital night without affecting significantly the power margin or ACS precision. The initial science results increased the interest in select targets and

reduced the importance of the all-sky survey; therefore, the night off-solar-pointing mode was instantiated to increase desired target availability.

In the default 3-axis ACS mode, attitude determination is accomplished via an Extended Kalman Filter (EKF) closed-loop process using inputs from coarse sun sensors, the medium sun sensor, a magnetometer, rate sensors built into the reaction wheels, and optionally the lunar sensor. Control is achieved using three orthogonal reaction wheels, plus a fourth skew wheel that is used as a backup control actuator in case any of the wheels fails. One of the orthogonal wheels is experiencing communications problems and has been swapped out in favor of the backup wheel. Momentum management is achieved by magnetorquers continually desaturating the reaction wheels. CHIPSat ACS performance is limited primarily by the sensors rather than the actuators; in other words, CHIPSat ACS control exceeds greatly ACS knowledge. The errors in ACS knowledge arise from several sources; in general, ACS knowledge precision is different between sunlight and eclipse portions of the orbit.

In sunlight, the medium sun sensor provides high fidelity in its two axes. Some error is introduced by Earth albedo in the MSS field-of-view that affects the apparent position of the sun. This error increases in magnitude until the Sun falls outside of the medium sun sensor's field of view. Typically, the error in the medium sun sensor, and therefore the CHIPSat ACS performance in the two axes perpendicular to the sun-line, is less than 0.5 degrees. In the third axis (about the solar-spacecraft vector), the ACS knowledge error is dominated by a combination of magnetometer and rate sensor error. In this axis, the knowledge error typically is less than two degrees.

In eclipse, without the medium sun sensor input and given that the magnetometer provides only two axes of information, the rate sensors must provide the third axis of ACS knowledge. The CHIPSat rate sensors drift with time and temperature; during sunlight, the rate sensor bias is estimated continuously using the input from the medium sun-sensor and magnetometer as required. But in eclipse, rate sensor bias estimation is disabled due to the lack of sun sensor input.

Therefore, the ACS knowledge drifts along with the rate sensor error, in addition to nominal magnetometer error. Typically, the knowledge error in eclipse is less than three degrees.

Both sunlight and eclipse ACS knowledge errors can be seen in the following plot:

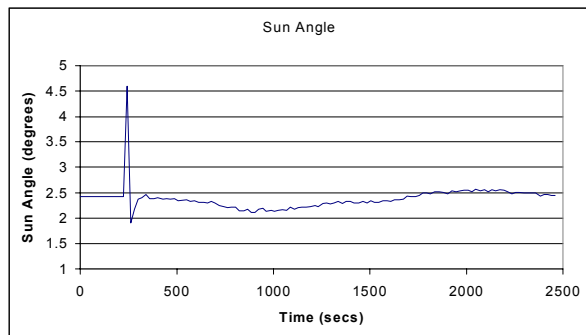


Figure 7: ACS knowledge errors

This plot displays the angle from the sun sensor boresight to the sun versus time for a section of one target observation. The calculated angle between the sun and the boresight of the medium sun sensor is approximately 2.5 degrees for this observation. At the start of the plot, the spacecraft is in eclipse – note that the calculated sun angle is constant as it is not updated in eclipse. After orbital sunrise, the initial sun angle is calculated at 4.5 degrees, instead of the expected 2.5 degrees, and the ACS must correct the spacecraft attitude by the 2-degree difference. This 2-degree error is likely caused by drift of the rate sensors during eclipse. After the initial sunlit correction, the sun angle is seen to drift by approximately 0.5 degrees roughly 1000 seconds into the plot, after which time the angle drifts back slowly. This drift likely is caused by Earth albedo in the field-of-view of the medium sun sensor.

Optimizing and Overcoming ACS Anomalies

During the first five months of CHIPSat on-orbit observations, several adjustments have been made to the ACS in order to optimize performance, and two adjustments have been made in order to correct for hardware anomalies. Due to the flexible ACS software implementation, it has been possible to upgrade both ACS parameters and the ACS code itself on-orbit based on initial performance evaluations. Early in the mission,

analysis of the ACS telemetry indicated possible optimizations in the alignment of ACS sensors; the relative weighting of the inputs of various sensors to the Extended Kalman Filter; and the raw signal values for which sensor outputs are declared valid. Changes to these parameters were made to the flight system after ground data analysis was used to determine optimal values.

To date, two unexpected algorithmic on-orbit behaviors have been observed in the CHIPSat ACS. First, a particular characteristic of the rate sensor bias estimation algorithm caused pointing inaccuracies for the specific case of the spacecraft slewing during the eclipse-entry penumbra. Specifically, the coarse sun sensor initially was used to update the rate sensor bias while the spacecraft was slewing for periods of time when the medium sun sensor did not produce a valid signal. During one slew that occurred during eclipse entry, the final valid coarse sun sensor signal contained a significant error likely caused by Earth albedo; as a result, the rate bias estimation was incorrect for the subsequent eclipse. The incorrect rate sensor bias estimation caused a bad ACS solution in the third, i.e. non-magnetometer-determined, axis during the eclipse. After noticing this behavior, and based on other factors (see below), the coarse sun sensor has been disabled except during initial ACS acquisition, which occurs during the first slew after the ACS computer boots.

The second unexpected ACS algorithm behavior occurs as a function of the seasonal variation of the solar-spacecraft vector with respect to the Earth's magnetic field. When the solar-spacecraft vector aligns closely with the magnetic field vector, the magnetometer is unable to provide ACS knowledge in the third axis (i.e. about the solar-spacecraft vector) for a portion of each orbit. While the rate sensors could be used to carry the ACS knowledge in the third axis during these time periods, the CHIPSat ACS uses the magnetometer and medium sun sensor to perform rate sensor bias estimation at all times when the spacecraft is sunlit. When the solar and magnetic vectors align, the rate sensor bias estimation is inaccurate in the third axis, which reduces the precision of the rate sensor information. As of June 2003, the CHIPSat team is in the process of evaluating whether or not

a correction should be made to the ACS software to account for this behavior. The most likely correction would be to disable rate sensor bias estimation when the solar and magnetic vectors align closely; the resulting rate sensor drift would be less than two degrees over the time period between bias estimation updates, which would improve the performance relative to the current situation of incorrect bias estimates.

Two ACS hardware anomalies have resulted in changes to the CHIPSat ACS configuration. First, one of the four onboard reaction wheels began to experience temperature-dependent difficulty communicating with the ACS control computer about two months into the mission. This behavior was seen during a brief interval of ground testing, just before the spacecraft was placed into the system-level thermal vacuum test chamber. Unfortunately, the behavior disappeared by the time that a debugging strategy had been developed, and did not reappear until on-orbit. At the time that the behavior was seen on the ground, schedule constraints did not allow the de-integration of the observatory that would have been required in order to investigate further the anomaly.

Once the anomaly resurfaced on-orbit, the debugging strategy was implemented. These efforts have pointed to a faulty crystal oscillator within the reaction wheel as the likely source of the asynchronous serial communications difficulties. While the reaction wheel is functioning nominally apart from the communications interface, the communications became poor enough for some operational temperature ranges that the ACS computer could not control the reaction wheel speed with enough bandwidth. This lack of control prevented correct 3-axis control of the spacecraft. At this time (in mid-June 2003), the ACS configuration parameters were modified in order to replace the faulty wheel in the active ACS algorithm with the fourth, redundant wheel. This wheel is located in the skew axis, so ACS control is slightly less efficient in the new configuration. Otherwise, the CHIPSat ACS performance has been unaffected by the switch to the new wheel configuration.

The second ACS hardware anomaly was seen in the coarse sun sensor, which consists of a set of six orthogonal photodiodes. One month into the mission, three of the photodiodes began to develop a bias such that the coarse sun sensor appeared to register a signal even in eclipse. After this bias developed, the coarse sun sensor was disabled in order to prevent possible erroneous ACS knowledge calculations. As with all ACS configuration modifications, table-driven command files were modified in order to disable the CSS; having this flexibility in the design eliminates the complexity of validating flight code changes. Approximately two months into the mission, the photodiode biases began to drop, and three months into the mission all photodiodes regained their nominal behavior. The coarse sun sensor remains disabled, however, except during initial ACS acquisition (see above). The cause of the temporary photodiode bias is unknown at this time.

Thermal Design and On-Orbit Performance

The CHIPSat spacecraft employs a passive cold-biased thermal design, with heaters to provide protection for critical subsystems. Software-controlled heaters are used to protect the spacecraft battery and payload. Thermo-statically controlled survival heaters are used to keep the battery, the flight computer, and reaction wheels within critical limits. The basis of the spacecraft thermal design was the isolation of hot and cold structure from CHIPS instrument and the avionics.

To accommodate the Delta-II SPE-2 launch configuration, CHIPSat required a compact, "turtle-shell" configuration. As a result, the main solar panels were very close to all spacecraft hardware making the thermal and mechanical designs a challenge. The structure was isolated generally using MLI blanketing with fiberglass washers and titanium bolts at most mechanical joints. Electronic boxes were thermally isolated from aluminum-honeycomb structure auxiliary panels using MLI blanketing, thermal tape, and fiberglass washers. The spacecraft avionics were thermally bonded to the Transition Adapter using layers of copper sheet. Individual slices within the electronic box stacks were bolted together, taped, and copper sheet applied to the backside. The

Transition Adapter, providing a radiator for the spacecraft avionics, was painted white and mostly covered by MLI. ACS components were also thermally isolated from the structure. The momentum wheels each had aluminum tape on the “top” as a radiator, MLI wrapped around the sides, and a heater bonded to the “bottom”. The surface treatment of the magnetometer was black anodized, and the sides were covered with MLI while the top received aluminum tape as a radiator.

The battery thermal control system was designed to be at an optimum temperature of approximately 10°C with a requirement to always stay between -10°C and +25°C. The two battery packs were required to be within 3°C nominally. The battery packs were mounted to equipment panels and auxiliary solar panels, but isolated using fiberglass washers. The battery packs were both thermally bonded to an aluminum strap that had a radiator in the middle. Individual battery cells were thermally bonded into aluminum clamshells to make packs of 5. The packs and strap were wrapped with MLI. The radiator had thermal tape and a clear field-of-view. Figure 8 shows a sustained period of on-orbit average daily temperature results for the battery.

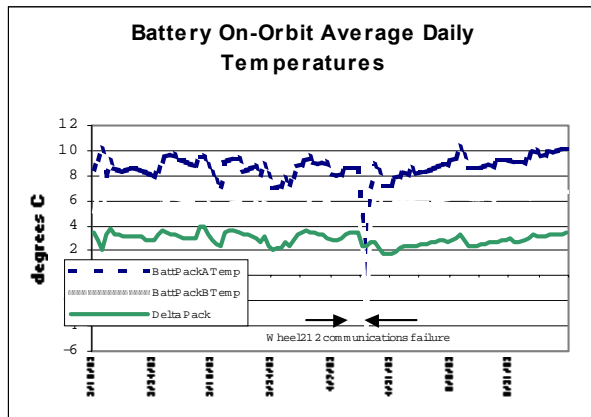


Figure 8: CHIPSat Battery On-Orbit Temperature Results

The Wheel #212 anomaly, resulting in the spacecraft tumbling for several days, caused the greatest temperature excursion to date. Nonetheless, data has shown that the battery continues to stay within its required operating range. More importantly, the temperature delta between the two 5-cell packs has consistently

maintained approximately 3 degrees for the life of the mission.

The CHIPS instrument, including its electronics box, is required to be maintained between -10°C and +35°C in an operational state and -20°C to +45°C in a non-operational state. Ideally, the electronics box should be maintained at or near room temperature at all times. In addition, optical alignment necessitates thermal gradients across the CHIPS instrument to be minimized. No thermal gradients greater than 5°C (1°C goal) can exist anywhere on the Main Optics Bench, the slit towers or gratings. The CHIPS instrument was wrapped in MLI and the three mounts were thermally isolated with G10 on both the instrument and spacecraft sides. The CHIPS electronic box was isolated from the structure similar to the other electronic boxes. Exposed surfaces were painted white and/or covered by MLI.

Figure 9 shows the “thermal blueprint” design of the CHIPS instrument from the +z direction.

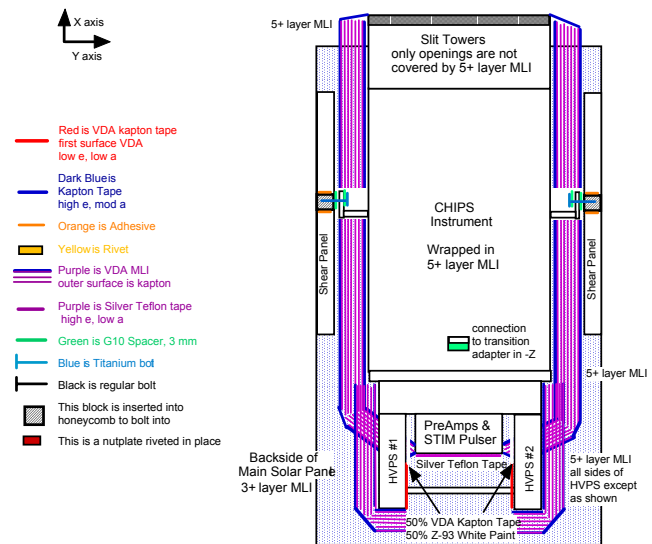


Figure 9: CHIPS Instrument External Thermal Design (+Z View)

Figure 10 shows the on-orbit average daily temperature results for 5 different locations on the CHIPS payload: slit entrances, the Upper Metering Structure (UMS), both High Voltage Power Supplies (HVPS) and the electronics box.

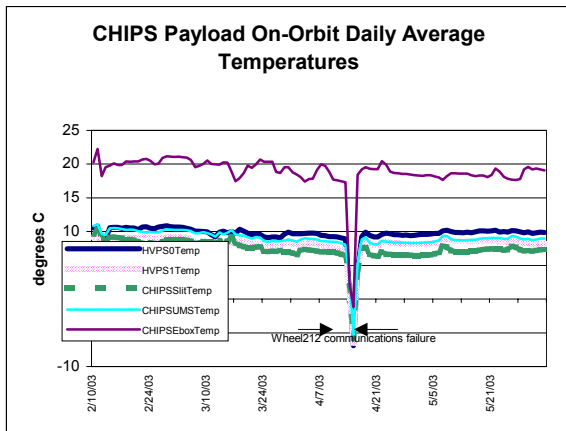


Figure 10: CHIPS Payload On-Orbit Temperature Results

Through the first five months of mission operations, the CHIPS payload has stayed well within temperature requirements with the electronics box being maintained around 20°C. During the Wheel #212 communication anomaly and resulting spacecraft tumble, CHIPS was load-shed, so the resulting temperature was more than 10°C within limits (-20°C). Finally, Instrument temperature measurements on either side of the Main Optical Bench show a gradient within 0.5°C thus meeting the gradient goal.

Conclusion

CHIPSat has been on orbit and performing well since mid-January 2003. Data from the instrument has already led to interesting scientific results. Overall, the mission has achieved the goal NASA initially set out for UNEX projects - to show that significant science and/or technology experiments can be performed with small satellites and in constrained budgets. However, getting CHIPSat to orbit had considerable challenges. The largest one was finding a credible launch opportunity. The CHIPS instrument was initially proposed to be part of the 'Secondary Payload Program' aboard a FAISAT commercial communications satellite. After concerns arose because of the satellite's scheduled launch on a Cosmos rocket, the mission was re-designed as a dedicated free-flyer to be launched on a Delta II GPS refurbishment mission as a secondary payload. However, modifications and a weight increase of the GPS primary payload made this option infeasible and CHIPSat finally

launched with the Delta II ICESat mission. In addition to the launch difficulties, designing a testable system that is robust enough for the space environment yet at an affordable cost and on schedule proved to be a constant challenge. To keep on cost, CHIPSat used COTS parts but employed an extremely robust systems design. To keep on schedule, the team found the use of the Internet to integrate sub-systems early in the project was a valuable tool.

Acknowledgements

Many people played significant roles in getting CHIPS to orbit. First and foremost, we'd like to thank the science and engineering teams at the Space Science Lab, SpaceDev, Inc and Dynacon, Inc who worked tirelessly over 3 years to make the project a success. In addition, we gratefully acknowledge the support from NASA's Goddard Space Flight Center for the resources they provided and the helpful feedback from their review teams. We would also like to thank the launcher teams at Boeing and Vandenberg Air Force Base for their support. We very much appreciate the ICESAT mission providing a ride for CHIPSat as a secondary payload. Finally, many other companies, organizations, and individuals (to numerous to list) provided hardware that has worked as designed, or invaluable services during the development effort.