The CHIPSat Spacecraft Design –
Significant Science on a Low Budget

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ABSTRACT

The Cosmic Hot Interstellar Plasma Spectrometer satellite (CHIPSat) was launched on January 12, 2003 and is successfully accomplishing its mission. CHIPS is NASA's first-ever University-Class Explorer (UNEX) project, and is performed through a grant to the University of California at Berkeley (UCB) Space Sciences Laboratory (SSL). As a small start-up aerospace company, SpaceDev was awarded responsibility for a low-cost spacecraft and mission design, build, integration and test, and mission operations. The company leveraged past small satellite mission experiences to help design a robust small spacecraft system architecture. In addition, they utilized common industry hardware and software standards to facilitate design implementation, integration, and test of the bus, including the use of TCP/IP protocols and the Internet for end-to-end satellite communications. The approach called for a single-string design except in critical areas, the use of COTS parts to incorporate the latest proven technologies in commercial electronics, and the establishment of a working system as quickly as possible in order to maximize test hours prior to launch. Furthermore, automated ground systems were combined with table-configured onboard software to allow for "hands-off" mission operations. During nominal operations, the CHIPSat spacecraft uses a 3-axis stabilized zero-momentum bias "Nominal" mode. The secondary mode is a "Safehold" mode where fixed "keep-alive" arrays maintain enough power to operate the essential spacecraft bus in any attitude and spin condition, and no a-priori attitude knowledge is required to recover. Due to the omnidirectional antenna design, communications are robust in "Safehold" mode, including the transmission of basic housekeeping data at a duty cycle that is adjusted based on available solar power. This design enables the entire mission to be spent in "Observation Mode" with timed pointing files mapping the sky as desired unless an anomalous event upsets the health of the bus such that the spacecraft system toggles back to "Safehold". In all conditions, spacecraft operations do not require any time-critical operator involvement.

This paper will examine the results of the first six months of CHIPSat on-orbit operations and measure them against the expectations of the aforementioned design architecture. The end result will be a "lessons learned" account of a 3-axis sun-pointing small spacecraft design architecture that will be useful for future science missions.

1. THE MISSION

CHIPS, the Cosmic Hot Interstellar Plasma Spectrometer, is the first NASA University-Class Explorer (UNEX) project. CHIPS was selected in 1998 and launched as CHIPSat aboard a Delta-II on January 12, 2003. The grazing incidence CHIPS spectrograph surveys the sky and records spectra of diffuse emission in the comparatively unexplored wavelength band between 90 and 260 Å. These data are providing important new constraints on the temperature, ionization state, and emission measure of hot plasma in the "local bubble" of the interstellar medium.

The CHIPSat spacecraft and CHIPS instrument operate largely autonomously with biweekly updates from the ground. CHIPS target planning software generates quaternion observation files that are executed by an onboard scheduling task. Data is autonomously downlinked, distributed and archived over secure links on the Internet. The spacecraft itself acts as a node on the Internet and autonomously performs data file management, power management, and momentum management. The spacecraft ephemeris is updated from

NORAD-supplied two-line element (TLE) sets. Each new TLE is checked by operators in the Mission Operations Center (MOC) prior to being incorporated into the next-scheduled upload to the spacecraft. The checking of the TLE includes a visual check of the TLE's authenticity by combining its predicted Keplerian elements against a set of trendlines from previous TLE sets. This helps avoid the use of 'rogue' ephemeris sets.

The baseline nominal sky survey coverage is achieved by aligning the instrument field of view roughly perpendicular to the sun line. The spacecraft is then rotated about the sun line to access various resolution elements, or resels. The primary coverage pattern, as is termed the "Chinese Lantern" comprising 316 resels (Figure 1).

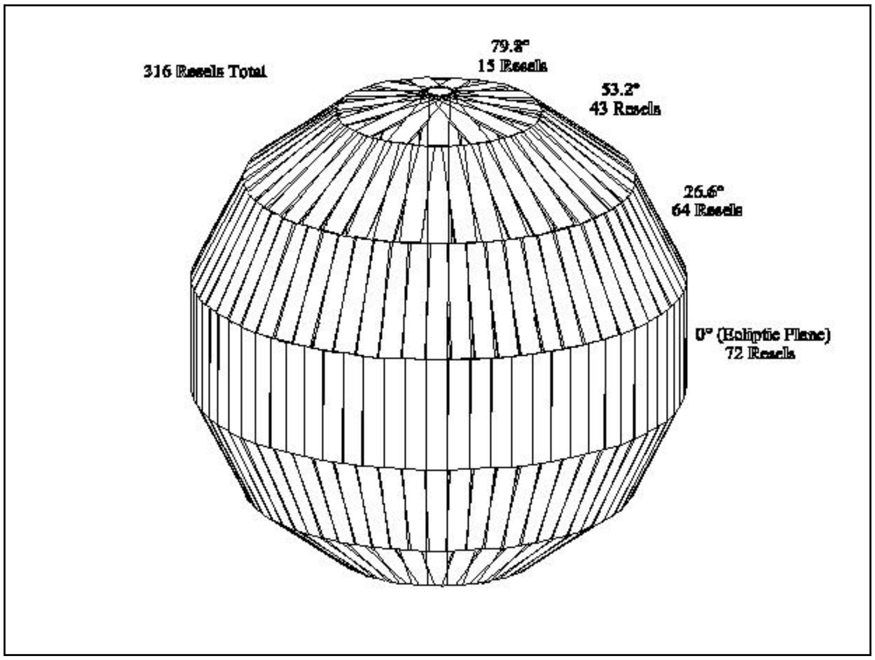


Figure1: Observation Strategy ("Chinese Lantern" Tessellation)

Each resel is defined as 5 degrees by 26.6 degrees rectangle projected on the sky, that is a rectangle constituted from great circle arcs. The long axes of each resel are aligned parallel to lines of ecliptic longitude. This configuration is shown in Figure 2.

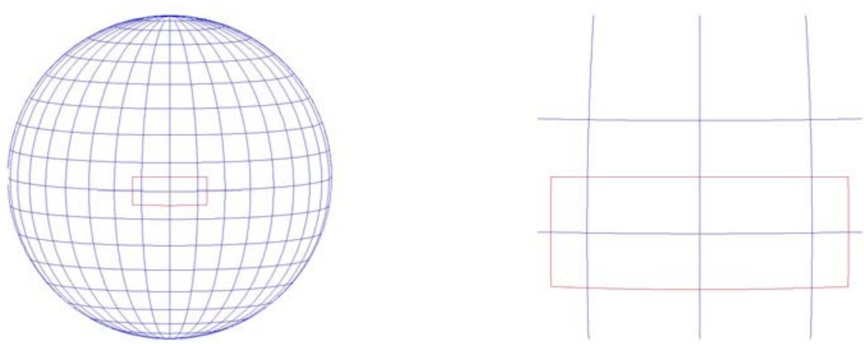


Figure 2: View of Rectangular Chips FOV (5° x 26.6°) Projected onto a Celestial Sphere

CHIPSat images resels when they are roughly perpendicular to the sun line. This simplifies the attitude control operation. It also provides the most consistent and easily achieved repeatability in resel orientation on the celestial sphere. The observation schedule for the celestial resels is generated by the science planning team at UCB. This schedule is then verified by the spacecraft operations team, which uses software that checks the observation schedule against various spacecraft and instrument operational constraints. Specifically, the angle between the instrument boresight and the sun, Earth, moon, and ram direction must fall within acceptable limits. During orbital day, the main solar panel must be pointed to within twenty degrees of the sun; the boresight of the science instrument may be rotated around the spacecraft-sun vector in any orientation. During orbital nights, the boresight may be pointed at any location on the celestial sphere.

While targets are selected based on science criteria that are re-evaluated continuously as on-orbit data is analyzed, a simulation performed prior to the mission verified that CHIPSat can observe all 316 resels – the entire sky – to 50,000 seconds depth in 356 days (requirement is less than one year). This simulation selected target resels by evaluating the longest available observation, taking into account slew times and the aforementioned spacecraft and instrument constraints. Resels deemed observable were matched against requirements for observation time and against their relative position within the hierarchy of available resels.

CHIPSat was a secondary payload whose launch resulted in a highly-inclined, near-sun-synchronous orbit near 600 km altitude. An advantage of the high inclination orbit is that most terrestrial ground stations are accessible. CHIPSat primary ground stations at Berkeley and Adelaide (University of South Australia) provided sufficient downlink for the expected data volume. NASA's WFF (Wallops Flight Facility) was added just before launch to provide redundancy and extra coverage during early operations. NASA since has authorized WFF to remain in use during nominal operations. A global view of CHIPSat's track and ground station coverage is provided in Figure 3.

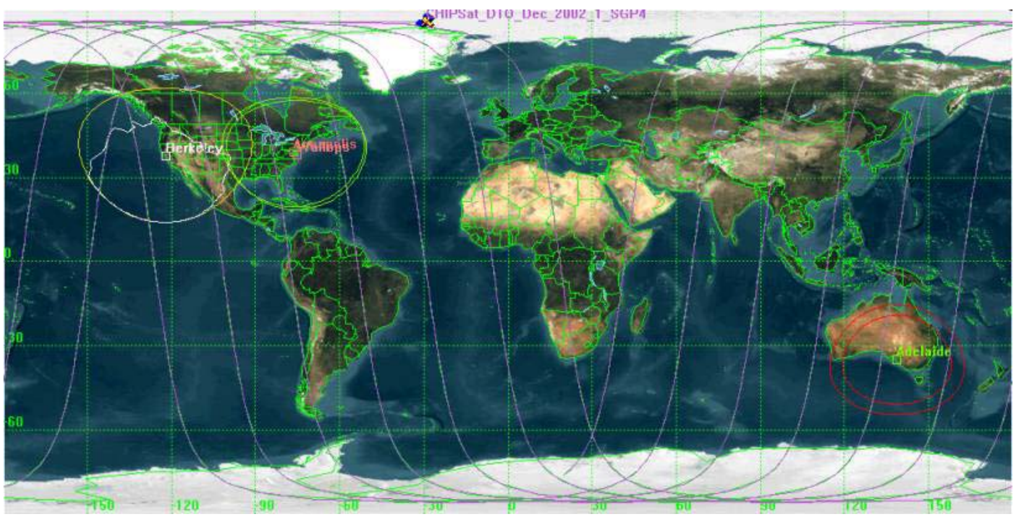


Figure 3: View of CHIPSat in 94 deg inclination LEO with available Ground Stations

2. THE SPACECRAFT

CHIPS is a very unique UV instrument in that it is attempting to fill a lack of spectral data required to more accurately represent plasma conditions in the local interstellar medium. The requirements for the spacecraft bus were such that a microsat (<100 kg, <50W to payload) could accomplish the mission. As a result, NASA, UCB, and SpaceDev embarked on a $13-15M and 2-3 year schedule project. With in-depth NASA oversight constantly enforcing that "failure is not an option", a spacecraft was successfully put into orbit and has operated successfully for over 200 days with an observing duty cycle greater than 95%. This is indeed an accomplishment for SpaceDev considering that it is the first domestic 3-axis controlled microsat to successfully operate in low-Earth orbit. How was this accomplished at such a reasonable cost?

2.1 APPROACH

SpaceDev developed a unique program philosophy to guide its CHIPSat, and hence, microsat program. The following principles were at the basis of the CHIPSat microsat:

- Simplicity -- the key to reliable and capable microsat designs is never to over-design the system. This philosophy should carry through to the software, ground segment, and mission operations as well as spacecraft hardware.
- Use past microsat experience to help and build a robust system. Microsats have been around for over 25 years, in which many organizations gained rich experience. SpaceDev leverages this experience and lessons learned to design its satellites. We use experienced personnel (graybeards, consultants) in an effort to learn from "old" mistakes.
- Rigorous selection & qualification of commercial components. Reliable systems can be built using commercial components provided that components are appropriate for use in the space environment and are made available early enough to ensure that adequate testing is performed at the subsystem and system level. A minimum "burn-in" testing goal for each component of 1000 failure-free hours was established.
- Radiation tolerance through tactical component selection and strategic system architectural design. For a benign orbit such as LEO, radiation tolerance can be achieved at the system level rather than on a component level.
- Component redundancy in general is not needed. If redundancy is desired, microsats are inexpensive enough to be implemented using multiple satellites, which increases redundancy at the mission level rather than at the spacecraft level.
- Modularity and scalability is required. Payloads suitable for microsats consistently come in various shapes, sizes, and bus requirements. Further, as a secondary payload, rideshares are common and with that comes the likely possibility of having to adapt to various launch platforms (some being completely unique) even during the development of just one satellite bus! The design needs to allow the timely replacement of parts, easy adaptations of new interfaces, and rapid reconfiguration.
- Implement cooperative decision-making, peer-to-peer oversight, and support for innovative thought. Small teams with each member wearing "multiple hats" are the fiscal reality so it is important to have each team member think and act like a systems engineer.

2.2 DESIGN

The CHIPSat design process started with identification of several key features that enabled SpaceDev to meet UCB's requirements and set the foundation for an establishing an advanced microsat capability in the U.S. These design features are summarized below:

- Receive commands in any spacecraft orientation – This is achieved by having the receiver always powered on and through the use of an omnidirectional antenna system.
- Realtime telemetry broadcast – In emergency or "Safehold" mode, this provides system diagnostics that do not require bidirectional communications
- System resetable without computer – This is achieved via a hardware command decoder which allows a back door reset of the system and a global watchdog timer to automatically reset the computer.
- No time critical operations – This is achieved by having solar arrays on all sides and eliminating the possibility of a death mode in any spacecraft attitude and tumble condition.
- Single-string, but survivable – Redundancy is included only for critical systems, such as the inclusion of a fourth reaction wheel and backup battery charging circuit

- Reusable and replaceable software -- All software is defined in separate modules and can be uploaded from the ground.
- 100% TCP/IP end-to-end communications architecture – Streamlines the software and ground segment development and eases the use of the same interface for integrated test as for on-orbit operations.
- Rigorous test program to prove new COTS-based SpaceDev avionics.

The CHIPSat bus is designed for use with sun-pointing missions and provides 3-axis control with an accuracy of better than 0.5 degrees when in sunlight. The bus avionics is centered around a PowerPC-based single-board computer (~50 MIPS / Watt performance, 160 MB SDRAM, 3U compact-PCI compatible) with an omnidirectional S-band communications system. Power is generated using a total of 35 solar array circuits composed of GaAs/GaInP/Ge dual-junction cells with a cell efficiency of ~23%. For the nominal sun-pointing orientation, EOL power available to the spacecraft bus is approximately 70W (orbital average). Power is stored onboard the spacecraft using a fiber-nickel-cadmium 14V battery, with a rated capacity of 6.5 AH. The avionics suite includes the central Single-Board Computer, Attitude Control System (ACS) Node, power control and distribution, telemetry, and thermal control units.

The CHIPSat S-Band transceiver is composed of a transmitter and separate receiver which are combined via a highly selective diplexer and split into two (RHCP & LHCP) antennas to provide near 4-Pi coverage. The system utilizes FSK modulation for both uplink and downlink, and utilizes rates of 4kbps-9.6kbps and 38.4kbps – 115.2kbps respectively.

The CHIPSat ACS is capable of operating in multiple modes. First, the attitude sensors can be used in a standalone fashion in order to provide attitude determination without any attitude control. Second, the ACS may operate to detumble the spacecraft by using a B-dot law with a magnetometer sensor and magnetorquer actuators. Finally, the ACS may operate in full 3-axis mode, with optional inclusion of the lunar sensor into the attitude solution. In 3-axis mode, attitude determination is accomplished via an Extended Kalman Filter (EKF) closed-loop process using inputs from coarse sun sensors, a 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 slew wheel that is used as a backup control actuator in case any of the wheels fails. Momentum management is achieved by magnetorquers continually desaturating the reaction wheels.

The spacecraft takes advantage of the innate capabilities and common tools of the Internet to manage time synchronization between the ground and the spacecraft. These include NTP (Network Time Protocol) on the SpaceDev TCP/IP data routers located at the ground stations and SNTP (Simple Network Time Protocol) running on the spacecraft operating system. The software running on the spacecraft periodically requests a time update from the ground station, and after a successful SNTP echo, the spacecraft clock is aligned to UTC (estimated at better than 100 milliseconds).

The 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, payload, and reaction wheels. In addition, thermostatically-controlled survival heaters are used to keep the battery and the computer within critical limits.

Instrument facilities include a payload bay, payload avionics deck, power, and serial data interface. The solar panels include three large nominal operation panels, and six keep-alive auxiliary panels that ensure the positive power budget under any bus attitude. Design and fabrication techniques allowed for a high level of cleanliness designed to support Class 100K molecular environments. The spacecraft launch vehicle interfaces included battery trickle charge and spacecraft payload purge. The spacecraft was launched in a power off configuration, and powered-on upon separation from the launch vehicle. Figures 4, 5 and 6 depict the CHIPSat spacecraft.

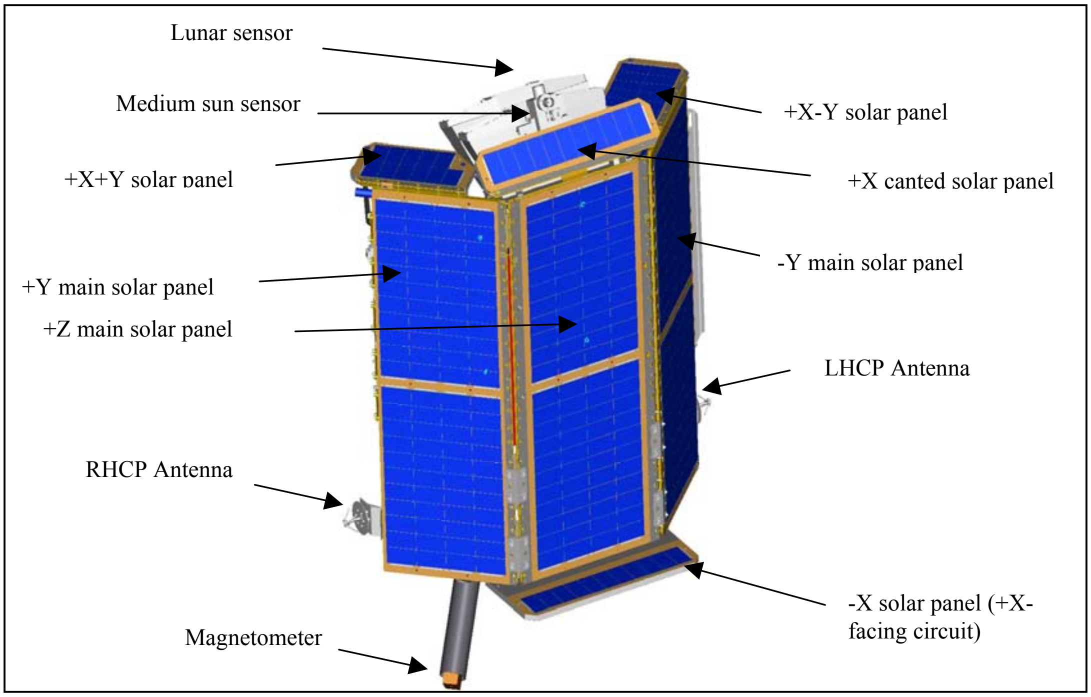


Figure 4: View of CHIPSat +Z Direction (main solar arrays)

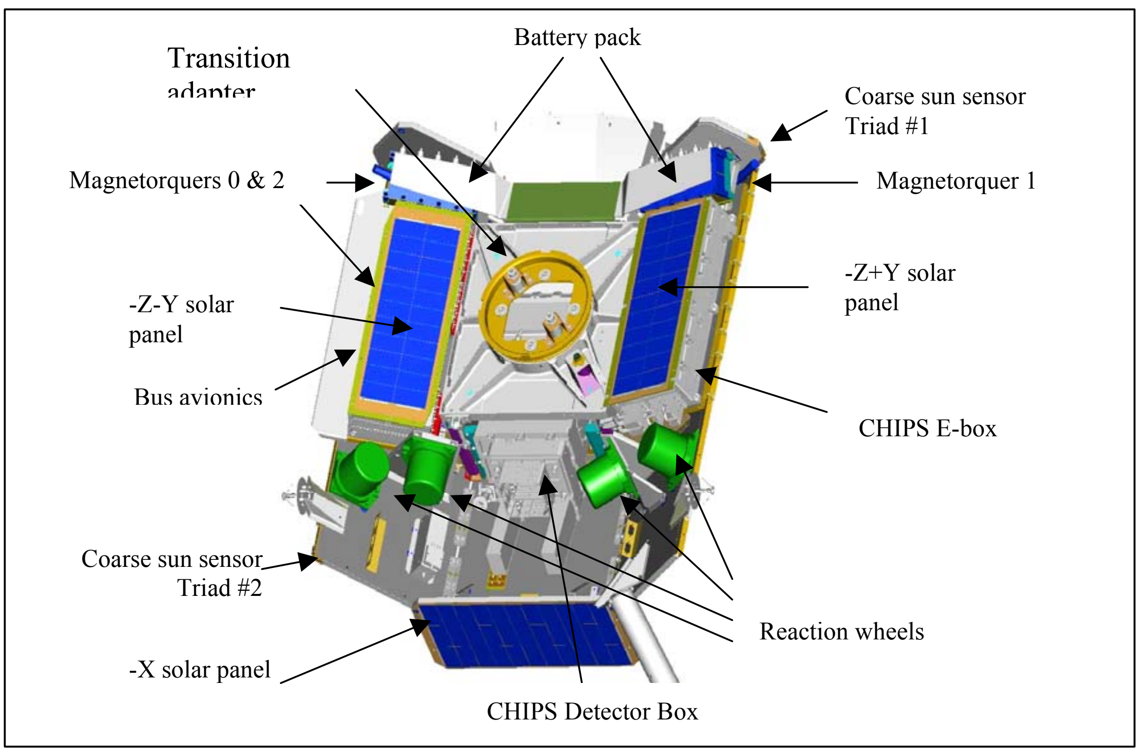


Figure 5: View of CHIPSat -Z Direction (auxiliary solar arrays)

Figure 6: View of CHIPSat prior to launch vehicle integration

The CHIPSat system provides a design that utilizes COTS philosophy. The avionics electronic components are primarily commercial grade with industrial temperature range. By adhering to a test program that included elevated temperature and 1000-hour burn-in testing on all spacecraft components, thermal stress screening, radiation testing, thermal cycling, and thermal vacuum, we could 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.

Furthermore, the use of COTS interface technologies simplified greatly 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. 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. Minimal custom code development was required at all levels including the on-board computer (C/C++ on VxWorks), the ground station router (C on Linux), and the mission control software (C/C++ on Windows NT). 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 mission control centers, science operations centers, and the spacecraft. The use of COTS Internet tools opened up a wide range of easily implemented operational capability including distributed and easily portable integration and test and mission operations.

3. THE RESULTS

3.1 OVERALL SYSTEM PERFORMANCE

During the first six months of the mission, the CHIPSat spacecraft has been able to perform per its design requirements. However, several anomalies (both expected and unexpected) have occurred. Since the start of science data collection, the net duty cycle for the acquisition of science data is approximately 95%.

Due to the use of non-radiation-hardened commercial electronics, some number of SEE's (Single-Event Effect) were expected. Even with the results of radiation testing that was performed during component development, it is difficult to predict the rate of on-orbit upsets. To date, the primary on-orbit SEE has been that the main flight computer resets on average every three-four 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 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 including the science observation schedule are resumed without requiring operator intervention.

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. The telemetry points that are subject to the spurious readings are used only in a limited fashion for spacecraft control, and even these points cannot affect the operations of the bus in a way that will interfere with nominal science data collection. 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.

Three anomalies have occurred to date relating to the onboard reaction wheels. CHIPSat is the second mission for the four microwheels (the first mission is FedSat); like the flight computer, the wheel design primarily employs commercial parts. One wheel incurred a communication failure; as a result, the spare wheel is being used for active ACS control. The failure is still under investigation, although initial analysis indicates a problem with the main crystal oscillator inside the wheel. An effort is underway to devise a software upload that can modify the communication method the wheel employs to regain its full capability. The two other anomalies were likely SEU effects; in one case, the spacecraft power system switched off one of the reaction wheels for an alleged overcurrent violation, while in the second case one of the reaction wheels appears to have crashed. In both cases, power cycling the relevant wheel caused nominal operations to be resumed.

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.

The mission lifetime requirement for the CHIPSat bus is 18 months. At this point in the mission, it is difficult to say what will be the limiting factor of total spacecraft lifetime. The entire power system is performing well above expected output since worst-case analysis was used in solar cell efficiency and power generation calculations. The NiCd battery was designed for 18 months (8,000 cycles per year) at 30% depth-of-discharge; so far, the spacecraft has been operating the battery at ~20% depth-of-discharge. To date, it has showed no signs of degraded performance.

3.2 ACS POINTING PERFORMANCE

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 is maximized at orbital noon and disappears at orbital sunrise and sunset (the sun and Earth albedo are collocated at such times). 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:

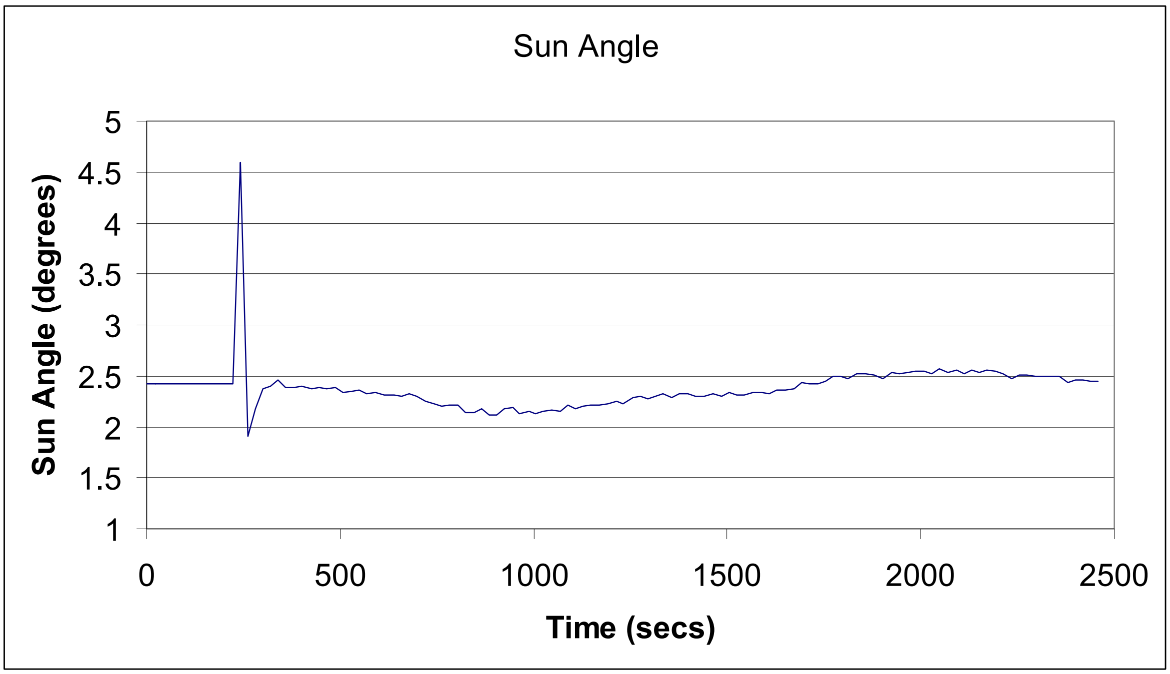
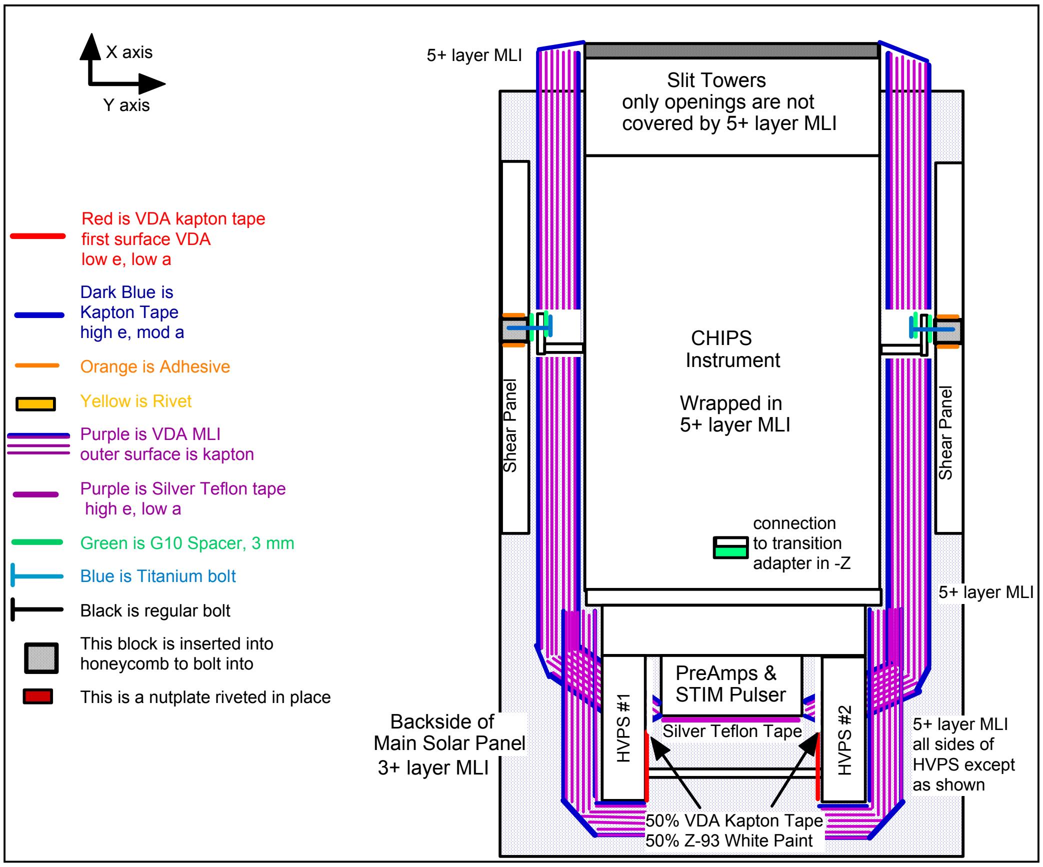


Figure 7: CHIPSat sun sensor boresight angle

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 was 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 is likely caused by Earth albedo in the field-of-view of the medium sun sensor.

3.3 THERMAL PROTECTION OF CHIPS

The payload, CHIPS, including its electronics box, is required to be maintained between –10C and +35C 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 degrees Celsius 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 8 is the "thermal blueprint"



design of the CHIPS instrument from the +z direction.

Figure 8: Thermal design of the CHIPS instrument (+Z direction)

Figure 9 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. The upper metering structure is located behind the Transition Adaptor (see Figure 5).

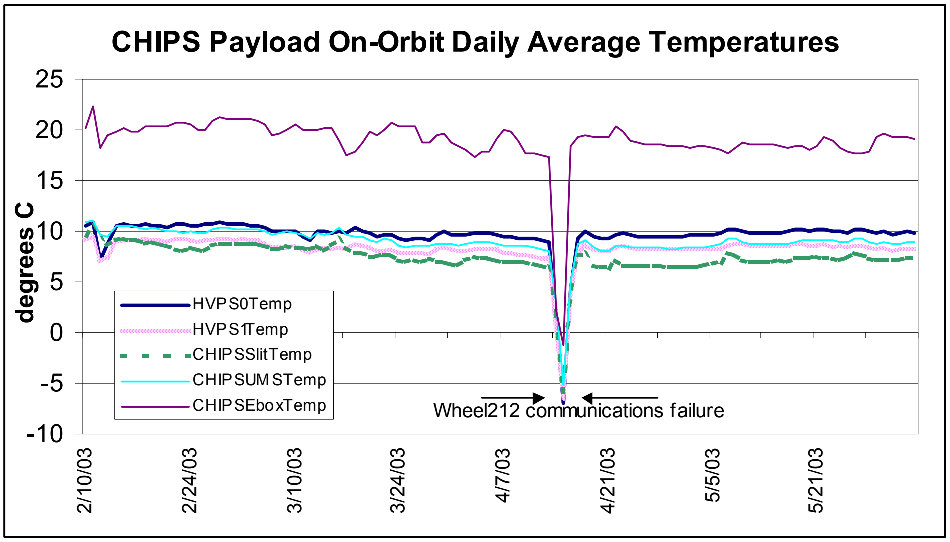


Figure 9: Average daily temperatures of CHIPS instrument

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 – near room temperature. During the initial appearance of the reaction wheel communication anomaly and resulting spacecraft tumble, CHIPS was load-shed, so the resulting temperature was more than 10°C within limits (-20°C). Last, the temperature measurements shown on the graph cover the dimensional extremes of the detector instrument and the result are clustered within 3-4 degrees thus meeting the gradient requirement.

3.4 ON-ORBIT COMMISSIONING AND ROUTINE OPERATIONS

Following the launch, each CHIPSat subsystem and its major components were checked out one by one via the same individual commands that were used during the I&T process. Once the operations team sufficiently verified the operation of all systems, they commanded the spacecraft to detumble by having it use the earth's magnetic field (B-dot law) to nearly eliminate its rotation rate. This detumble process took 2-3 orbits (~200 minutes). Once detumbled, the spacecraft was commanded to determine its on-orbit attitude and slew to point the main solar panel at the sun. Next, a sequence of regular pointing commands (with several slews per orbit) were uploaded and tested. Finally, the CHIPS instrument was powered on and commissioned, again with a step-by-step buildup to the operational configuration.

The actual CHIPSat commissioning took approximately 11 days because the project team very cautiously and slowly checked out all elements of the satellite prior to commencing closed-loop attitude control operations. Since it was a NASA science mission and SpaceDev's first satellite with many spacecraft components that had not flown before, this was the most appropriate choice. For future commissioning, a full checkout of all the spacecraft's subsystems, sensors, and actuators can be accomplished in a sequence of batched commands that would take a much shorter time to accomplish. Nonetheless, operations personnel requirements were relaxed so that commands were sent primarily during daytime and non-weekend hours. Since the exact same spacecraft commands using the exact same mission operations hardware and software were tested on the ground prior to launch many times (especially during thermal vacuum testing), 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 to allow for automated data limit checking. An emergency paging function was implemented to lessen the operations personnel requirements even further.

4. THE CONCLUSION

For a reasonable cost and on a fairly responsive schedule, the CHIPS project has managed to deliver data to NASA and the rest of the scientific community. SpaceDev's microsat design approach and design features were a major part in making this breakthrough mission a reality. The results, albeit only a little over 200 days old, prove that innovation in integrating COTS technologies in hardware, software, and end-to-end communications can reduce mission overhead and result in a robust system. CHIPSat is SpaceDev's building block for further advancements and added capabilities in spacecraft design. The additional on-orbit data will further enhance future designs and implementations. Most important, a vehicle now exists that grants access to numerous small science missions at an affordable cost.