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Conducting Science with a CubeSat: The Colorado Student Space Weather Experiment

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ABSTRACT

Energetic particles, electrons and protons either directly associated with solar flares or trapped in the terrestrial radiation belt, have a profound space weather impact. A 3U CubeSat mission with a single instrument, the Relativistic Electron and Proton Telescope integrated little experiment (REPTile), has been selected by the National Science Foundation to address fundamental questions pertaining to the relationship between solar flares and energetic particles. These questions include the acceleration and loss mechanisms of outer radiation belt electrons. The Colorado Student Space Weather Experiment operating in a highly inclined low earth orbit, will measure differential fluxes of relativistic electrons in the energy range of 0.5-2.9 MeV and protons in 10-40 MeV. This project is a collaborative effort between the Laboratory for Atmospheric and Space Physics and the Department of Aerospace Engineering Sciences at the University of Colorado, which includes the integration of students, faculty, and professional engineers.

INTRODUCTION

Solar flares have a direct impact on the near-earth space environment by causing physical changes in the density and ionization of the upper atmosphere, leading to enhanced drag on satellites in low earth orbit (LEO), communication disruptions, and degradation in the accuracy of the critically important Global Positioning Systems (GPS). Energetic particles, mostly protons, coming from the Sun are often associated with flares. Knowledge of the flare location on the Sun has important implications in predicting if, and how significantly, these solar explosions will affect earth. Energetic particles near the solar disk center are known to have more dramatic impacts on earth than those near the solar limb. Coronal Mass Ejections (CMEs), which sometimes occur with solar flares, can also produce energetic particles near the solar surface and beyond and can cause large geomagnetic storms. Relativistic electrons (100s keV to multiple MeV) trapped in the magnetosphere, often referred to as “killer electrons” due to their potential damage to spacecraft subsystems and to astronauts in space, have their largest variations during magnetic storms. Knowing the loss rate and the spectral evolution of these electrons will help us understand the underlying acceleration mechanisms.

The Colorado Student Space Weather Experiment (CSSWE) includes the Relativistic Electron and Proton Telescope integrated little experiment (REPTile). This instrument will measure energetic protons and electrons emanating from both the Sun and the Earth’s radiation belt.

The CSSWE is 3U CubeSat configuration and is being designed by students at the University of Colorado under the direction of faculty and staff. A two semester projects based space hardware course is being offered in the Aerospace Engineering Sciences (AES) department and cross-listed in the Electrical, Computer and Energy engineering department. Graduate students who enroll in the class will participate in one or more specific phases of the project. The project is currently nearing the critical design phase and this paper describes the current system architecture and state of the design.

SCIENCE BACKGROUND

Humankind has been fascinated with the Sun and its relationship to our planet. Sabine[1] was first to note that geomagnetic activity tracks the 11-year solar activity cycle. The first solar flare ever observed, in white light, was followed about 18 hours later by a very large geomagnetic storm[2]. The existence of the earth’s

radiation belts was established in 1958 by James Van Allen and co-workers using simple Geiger counters on board the Explorer-1 and -3 spacecraft[3]. Since then, more advanced space missions have provided insight into the phenomenology and range of processes active on the Sun and in the radiation belts.

We now understand that CMEs, which are episodic ejections of material from the solar atmosphere into the solar wind, are the link between solar activity and large, non-recurrent geomagnetic storms, during which the trapped radiation belt electrons have their largest variations. There is a strong correlation between CMEs and solar flares, but the correlation does not appear to be a causal one. Rather, solar flares and CMEs appear to be separate phenomena, both resulting from relatively rapid changes in the magnetic structure of the solar atmosphere[4].

Solar flares are very violent processes in the solar atmosphere that are associated with large energy releases ranging from 10^{22} J for sub-flares, to more than 10^{32} J for the largest flares[5]. The strongest support for the onset of the impulsive phase is due to magnetic reconnection of existing or recently emerged magnetic flux loops[6]. Reconnection accelerates particles, producing proton and electron beams that travel along flaring coronal loops. Some of the high-energy particles (SEPs) escape from the Sun to produce solar energetic particle events, which will be measured at earth by REPTile. The particle beams that travel deeper into the solar atmosphere produce impulsive phase flare X-ray emissions. Measurements of these X-rays will be made by SDO-EVE and/or GOES-SXI and will be used to identify flares for comparative studies with REPTile SEP measurements.

SEP measurements are important for space weather applications because of their direct effects in earth's ionosphere and on manmade systems in space. SEP and CME particles, if they arrive at earth, enhance the ionosphere, primarily at high latitudes. These ionospheric changes lead to a myriad of space weather consequences, such as degradation or even disruption of communications, degradation in the accuracy of the highly relied upon Global Positioning System (GPS)[7], and surges in our power lines on the ground that could lead to widespread blackouts.

The earth's radiation belts are usually divided into the inner belt, centered near 1.5 earth radii (RE) from the center of the earth when measured in the equatorial

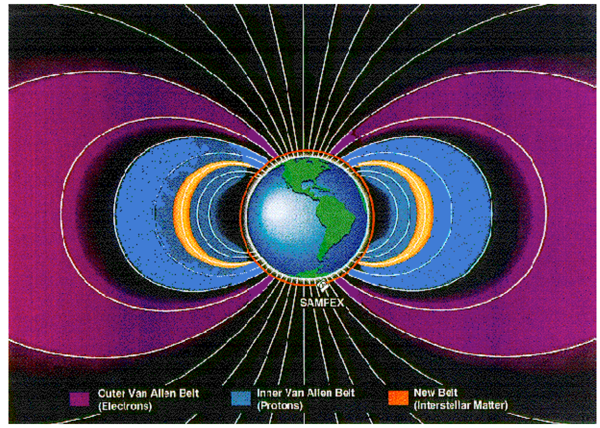

Figure 1: Schematic cross section of the trapped radiation belts surrounding Earth. The inner and outer Van Allen belts are shown in blue and purple. The two yellowish crescents represent trapped energetic heavy nuclei that originated in the local interstellar medium, though their intensity is much lower than inner and outer belts. The white lines represent earth's magnetic field lines, approximated as a dipole. The orbit of the polar-orbiting SAMPEX satellite is indicated[10].

plane, and the outer radiation belt that is most intense between 4 and 5 RE. Fig. 1 shows a schematic illustration. These belts form a torus around the earth, and many important orbits go through them, including those for GPS satellites and spacecraft GEO and in highly inclined LEO.

Earth's outer radiation belt consists of electrons in the energy range from a few keV to MeV. Compared to the inner radiation belt that usually contains somewhat less energetic electrons but an extremely intense population of protons extending in energy up to several hundreds of MeV or even GeV, the outer belt consists of energetic electrons that show a great deal of variability which is well correlated with geomagnetic storms and high speed solar wind streams[8,9].

MISSION OVERVIEW

The scientific objectives of the Colorado Student Space Weather Satellite (CSSWE) are to understand

1. *How flare location, magnitude, and frequency relate to the timing, duration, and energy spectrum of SEPs reaching Earth*
2. *How the energy spectrum of radiation belt electrons evolve and how this evolution relates to the acceleration mechanism.*

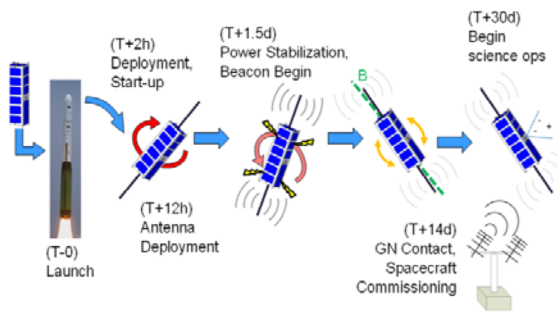

Figure 2: Early operations and commissioning concept of operations for CSSWE.

To accomplish these goals CSSWE has a requirement for a minimum of 3 months of science operations based on expected flare and geomagnetic storm frequency. The first month of operations will be utilized for systems stabilizations and check out. **Error! Reference source not found.** outlines the early mission operation schedule for the CSSWE mission. CSSWE will be deployed from a standard Poly Picosatellite Orbital Deployer (P-POD)[11] and will initially be tumbling at an unknown rate and attitude. Sufficient power will be available after two orbits to power up the command and data handling system (C&DH) and deploy the stowed communications antennas. Over the first 14 days the passive magnetic attitude system will align the CubeSat with the local magnetic field. During this time the batteries will continue to charge. Once a sufficient state of charge has been achieved the communications beacon will be initiated. This beacon will be initiated no later than 36 hours after launch for early operations and tracking.

Within 14 days of launch, the system will have attained a stable attitude configuration whereby commanding of the spacecraft can be initiated. During the next 14 days system checkout will be conducted with science operations scheduled to begin 30 days after launch. The system will operate in a single science mode with data being collected continuously from REPTile with the exception of periods when ground contacts are occurring.

SYSTEM OVERVIEW

CSSWE is designed to adhere to the Cal Poly CubeSat design specifications for a 3U CubeSat[11]. The maximum mass and dimensions as described in the design specifications are 10cmx10cmx34cm and 4kg. Figure 3 shows a SolidWorks model of the 3U CSSWE CubeSat. The current design iteration has all four long sides of the CubeSat covered with Emcore triple junction 28% efficient solar cells. In this configuration eight cells are located on two of the 3U sides, and six cells are located on the remaining two 3U sides, with no cells on the two 1U sides on the ends of the CubeSat. The justification for this arrangement is twofold: removing solar cells from two of the four sides surrounding the electronics box allows the electronics to radiate excess heat. A lack of solar cells on the ends of the craft also allows the antennas to be mounted properly to ensure the antennas are deployed smoothly.

The major subsystems in CSSWE are the command and data handling (C&DH), electrical power (EPS), communication (COMM), attitude determination and control (ADCS), thermal (THM), structure (STR) and software (SFT). A set of top level system requirements for CSSWE were developed based on the mission goals that were discussed in the previous section. The system requirements were then flowed down to subsystem requirements. In addition to this system level decomposition clear interfaces were defined and an interface control document was developed to manage all of the electrical, mechanical and software interfaces between subsystems.

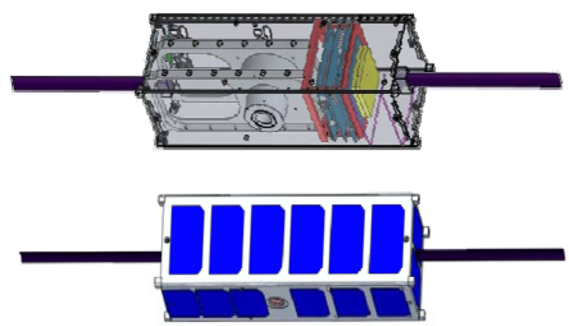

Figure 3: Solid model of CSSWE showing deployed communications antennas, solar panel configuration and internal structure.

Figure 4 shows the system block diagram for CSSWE and electrical interfaces between all of the subsystems. CSSWE has two onboard microcontrollers, one within the COMM subsystem and the second in the C&DH subsystem. The C&DH MCU is responsible for commanding the spacecraft and storing data, while the COMM MCU decodes signals from the ground network and ensures that the C&DH subsystem is working properly. To this end, the MCU will monitor the spacecraft bus along with the communications link and if extended inactivity is detected via the expiration of a watchdog timer, the C&DH system will be reset by the COMM system. C&DH is responsible for collecting science data from both REPTile and the magnetometer, along with managing housekeeping data which are stored within its flash memory. EPS supplies conditioned power from the solar cells when insolated and from the battery when in eclipse. Additionally EPS

has the task managing all aspects of battery charging and health.

There are two passive systems on CSSWE, these are the thermal and attitude control system. Thermal control is accomplished via Kapton tape on all exposed (non-solar cell covered) areas of the CubeSat. The passive attitude control system uses the magnetic torque of a bar magnet against the earth's magnetic field and a set of hysteresis rods to align the satellite to within 15 degrees of the local magnetic field. More details on each of these subsystems in contained in the following subsections of the paper.

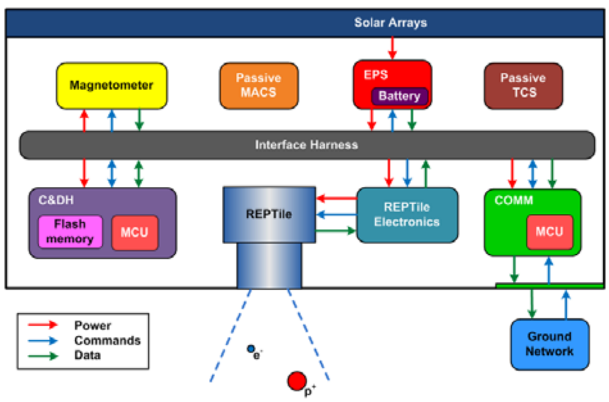

Figure 4: A system block diagram of CSSWE indicating major subsystems and interfaces.

MASS, POWER AND VOLUME BUDGET

Mass, power and volume are limited resources on CubeSats. Being limited to a 4kg wet mass, a volume of 3400 cm^3, and a surface area of 1560cm^2 can create a major design challenge. In the original design CSSWE had a second solar instrument that required pointing on the order of 1^o. While achievable, the resources required to reach this level of fidelity created negative mass and power margins. As a result, the solar instrument was descoped early in the project thus providing sufficient mass and power margins for the remaining REPTile instrument. In fact additional shielding was required for REPTile to achieve the required off axis particle rejection. Without the descope of the solar instrument we would not have been able to accommodate the additional mass requirement for shielding that the REPTile instrument required.

Table 1 shows the current mass, power and volume estimates for each of the subsystems shown in Figure 4. As can been seen in the table the spacecraft structure and the REPTile instrument make up nearly 75% of the system mass. The current mass margin is in excess of 30% which is sufficient as we approach a CDR level design.

With most of the mass in either the aluminum and tungsten shielding for the REPTile instrument or the structure less than 25% of the total volume is utilized. The underutilization of the volume will aid in flexibility for integration tasks and routing of harnesses. Note that requirement 2.2.17 of the CubeSat design specifications[11] state that "The CubeSat center of gravity shall be located within a sphere of 2 cm from its geometric center." This requirement drives the placement of the REPTile instrument near the geometric center of CSSWE.

Table 1: Mass, power and volume budgets for CSSWE.

Subsystem	Mass (g)	Volume (cm^3)	Power (mW)	
			Insolated	Eclipse
Structure	840.9	310.8	0	0
EPS	380.3	116.1	3116	153
C&DH	88.3	32.5	340	340
REPTile	1209.6	184.5	920	920
COMM	109.3	25.5	713	758
ADCS	19.1	12.0	2	2
Interface	100.0	84.9	0	0
Total	2747.5	766.3	5091	2173
Available	4000	3400	6750	2934
Margin	**31.3%**	**77.5%**	**24.6%**	**25.9%**

STRUCTURE (STR)

Figure 5 shows the evolution of the CSSWE structural design over the course of the spring 2010 semester. In the original design, the REPTile instrument was fixed in the center of the exterior shell using three vertical plates and two horizontal supports. Analyzing this configuration led to an important improvement in the overall design. With dimensions of only 10 x 10cm, it would be difficult to integrate components into the center of the structure. This issue led to the addition of the support legs seen in the March 19th revision. The four legs vertically support the weight of the REPTile and electronics boards, allowing for a freestanding internal structure when the exterior shell slides off. With the "skeleton" free from the external shell, subsystem integration and wiring becomes much simpler.

One major drawback of this design was the number of individual pieces that needed to be machined, the required setup time and the potential for tolerance stack-up. Thus a second iteration of the structure was introduced. This version labeled April 9th was designed to be milled from a single block of aluminum. While strong and light this design led to a concern about manufacturing cost and complexity. As a result a fourth iteration was developed and is labeled April 30th in Figure 5. The final internal skeleton is now composed of three parts which include two large vertical plates that act as the REPTile mounting supports and one upper ring that supports the electronic board stack. The spacecraft will be nearly fully integrated, with the exception of the top endcap, before being slid into the outer casing. Because deployment of the CubeSat is critically dependent upon the external CubeSat structure which interfaces to the P-POD, the CSSWE team opted to use the 3U solid wall structure provided by Pumpkin Inc.

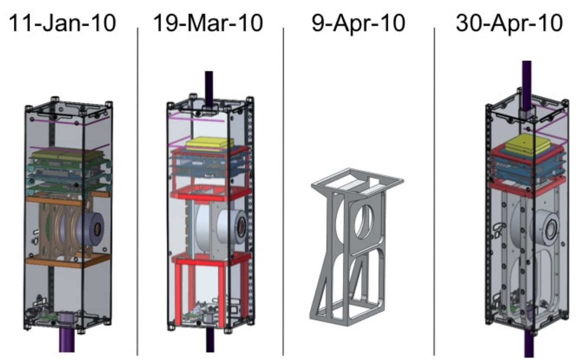

Figure 5: Evolution of the CSSWE internal structure.

The electronic boards also presented an interesting design challenge for the structural team. Similar to the REPTile instrument, the boards must be aligned inside the tight external shell. To solve this issue, the team integrated the electronics boards with the skeleton design through the use of commercially available board standoffs. The standoffs align each board vertically at all four corners, creating a simple stack attached to the top of the skeleton. The standard standoffs are used in conjunction with 104 pin headers to create an efficient bus between all of the boards. The standoffs also provide a reasonable thermal path for heat dissipation on-orbit. Finally, the stack approach allows the team to easily add extra boards in the future if any of the subsystem cannot fit all components on a single PCB.

SCIENCE (REPTILE)

The *R*elativistic *E*lectron and *P*roton *T*elescope *i*ntegrated *l*ittle *e*xperiment (REPTile) instrument has been designed to meet the science goals and requirements of the CSSWE CubeSat mission. The instrument will measure solar energetic protons from 10 to 40 MeV and outer radiation belt electrons from 500 keV to >3 MeV. Being the primary instrument on a CubeSat mission, it has been designed to be low mass (< 1.5 kg) with low power-draw (< 1.5 W).

Figure 6 shows how REPTile is integrated into the rest of the system. Four solid state detectors provide the initial signals when they are impacted by incoming particles. A series of amplifiers (charge sensitive amplitudes and operational amplifiers in Fig. 6) amplify and shape the signal such that it can be passed through a series of comparators to determine the particle type and incident energy based on calibrated reference voltages. A CPLD processes the comparator outputs and increments the appropriate count bin. C&DH reads and resets these CPLD bins every 6 seconds. These totals for each particle type and energy channel are stored as the raw data from the instrument.

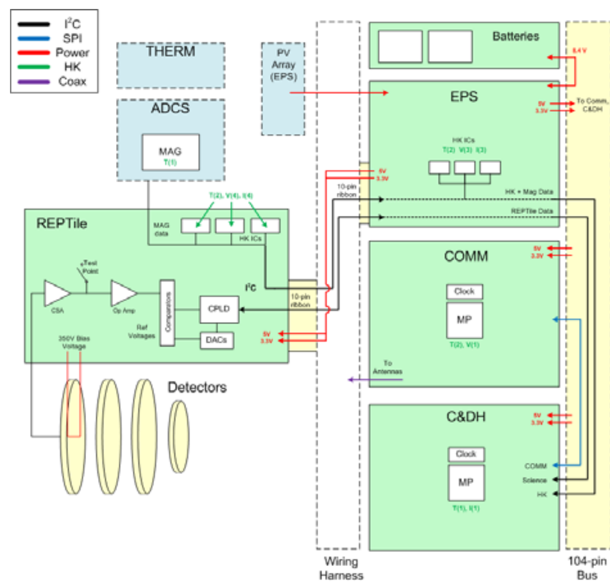

Figure 6: Electrical block diagram of the REPTile instrument and the related CSSWE subsystems.

REPTile is a heavily-shielded particle telescope designed to limit signal particles to a specific field-of-view (FOV), which is important for the science requirements, and great care has been taken to develop the instrument in such a way that it meets the strict mass and volume restrictions imposed by CubeSat requirements without sacrificing the instrument's

performance.

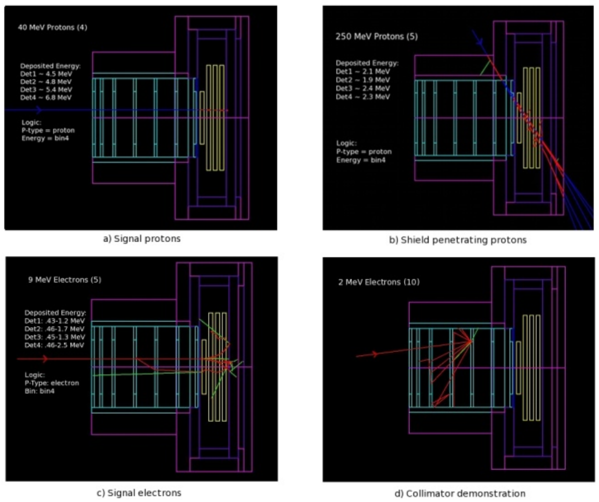

Figure 7: Geant4 simulations of particle interactions and secondary particle and photon generation in the REPTile instrument.

Many factors must be taken into consideration when designing an instrument to measure relativistic particles in earth's magnetosphere. Most important are the impact of secondary radiation, shield-penetrating particles, and electron scattering. To quantify these effects and the instrument performance itself, Geant4 software has been employed to simulate energetic particle interactions within the instrument's various materials. Using this tool, key parameters such as collimator length and diameter, collimator baffles, and shielding thicknesses, have been designed and the instrument performance quantified. Figure 7 shows examples in which Geant4 has been run with the current instrument geometry. In this figure different instrument materials are shown in different colors, and incident particles are shown with the colored tracks through the instrument itself (protons in red, electrons in blue, and high-energy photons in green). Also included are the energy and type of the incident particle beams, the average total energy deposited in each of the four detectors (yellow rectangles), and the particle type and energy bin into which the particles are categorized by the instrument electronics. Figure 7 also demonstrates the critical effects that must be accounted for in high-energy particle detector designs. In case b high-energy protons are shown to have the capability to penetrate through the layered shielding and appear as lower-energy, signal protons when the electronic logic is applied to their results. Also, in cases c and d, secondary radiation (i.e. the high-energy photons) and electron scattering are effectively demonstrated, which provide justification for layered shielding and collimator baffles.

From the Geant4 simulations, the REPTile design has been finalized. Figure 8 shows a cross-section of the instrument. Four detectors reside within a double-layered cylinder of shielding. The outer-layer of this shielding consists of aluminum, while the inner layer is tungsten. This double-layer design mitigates secondary radiation from high-energy particles incident on the shields. The dense tungsten is particularly effective at slowing and stopping high-energy particles, and the low-Z aluminum slows the incoming particles with the generation of significantly fewer secondary particles than if only one layer of high-Z tungsten was used. The instrument's collimator creates a ~50 degree FOV. Here, baffles prevent electrons coming from outside of this FOV from scattering into the detector stack (as can be seen in Figure 7 case d), and tantalum is used as the dense, particle stopping material to mitigate noise from particles penetrating through the collimator itself. A beryllium-foil "window" is employed as a high-pass energy filter for the incoming particles. The thickness of this window means electrons below 400 keV and protons below 9 MeV are blocked.

With this design, REPTile will provide four channels of differential fluxes of solar energetic protons ranging in energy from 10 to 40 MeV and three channels of differential fluxes and one of integral fluxes for radiation belt electrons with energies from 0.5 to >3 MeV. Instrument count rates, electronics capabilities, and signal-to-noise ratios have also been estimated using a series of Geant4 simulations and relevant flux environments at LEO, and these confirm that REPTile will meet the CSSWE science requirements and perform as designed on-orbit by achieving estimated signal to noise ratios in each energy channel ranging from 2.2 (4th bin protons) to 87.9 (1st bin electrons).

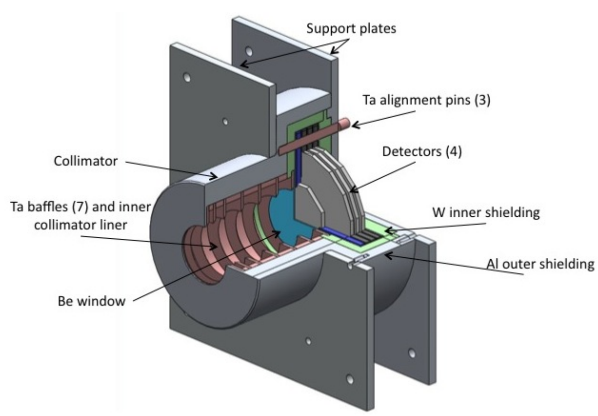

Figure 8: Mechanical design of the REPTile instrument.

ELECTRICAL POWER SYSTEM (EPS)

The EPS is required to deliver power to all electrical subsystems and to protect other subsystems from transient electrical behavior that originates in EPS. The system draws power from a photovoltaic array on the exterior of the spacecraft and delivers that power to the electrical subsystems of CSSWE. There is also a battery bank for storing energy and delivering that energy when the spacecraft is in eclipse. A high-level block diagram view of the circuitry within EPS is shown in Figure 9.

CSSWE uses 28 photovoltaic cells distributed among its 4 long (3U) sides, with an effective area of 763 cm^2. These are Emcore triple junction cells with a minimum rated beginning of life efficiency of 28%. Assuming 55° inclination and 600km altitude, Satellite Tool Kit (STK) models have shown the CubeSat generates 6.75W while insolated for 67% of each orbit. The solar cells are linked in 2 serial and 3 parallel (2s3p) and or 2 serial and 4 parallel (2s4p) configurations, where two cells connected in series provide 4.6V to the power system. However, the batteries require a constant current to charge without damage, thus a Battery Charge Regulator (BCR) is used. A boost converter is used to convert the 4.6V supplied by the solar cells to 12V required by the BCR. This circuit provides a constant 1 ampere current to the battery bank until the battery bank is fully charged. Two Lithium-Ion or Lithium-Polymer batteries, specific cells are yet to be determined, will store up to 14.8 W-hr generated by the solar cells. Each Li-Ion can operate at a maximum of 4.2 volts. These cells will be connected in series to supply between 6 and 8.4 volts (nominally 7.4 volts) to the power system.

Downstream from the battery bank are two buck converter circuits, each built around the LT3480 DC-DC converter IC. One of these circuits converts the battery voltage to 3.3 volts, and the other converts it to 5 volts. These voltages are made available to all other electrical subsystems, with solid-state switches to protect against overcurrent conditions and passive LC low-pass filters to protect against transient electrical behavior originating in the converter circuits. A 350 volt bias is also provided to each REPTile detector individually via a COTS DC-DC converter module, the EMCO Q04-5 converter. The 2.6 volt input to each of these modules is provided by using a MIC5203 linear regulator IC, which is connected to the 3.3 volt bus at its input.

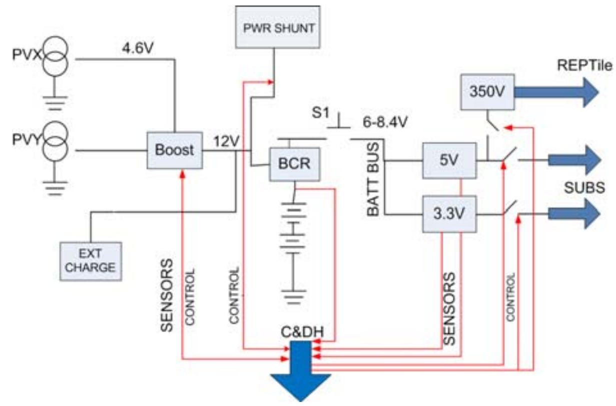

Figure 9: Electrical power system block diagram.

ATTITUDE DETERMINATION AND CONTROL SYSTEM (ADCS)

When studying energetic particles (electrons and protons) in the earth's magnetic field, a spacecraft attitude aligned with the earth's local magnetic field is the most useful. Also, a stable attitude is important for maintaining a communications link between the ground and the satellite. The ADCS system onboard CSSWE will align the CubeSat to within ±15° of the earth's local magnetic field within 7 days of launch. To meet these requirements, a simple passive magnetic attitude control (PMAC) system will be used. This system consists of a permanent bar magnet in combination with hysteresis rods. The bar magnet interacts with the local magnetic field to torque the spacecraft toward the local magnetic field direction. As the spacecraft progresses in its orbit, the local magnetic field induces a changing magnetic moment in the hysteresis rods. The soft magnetic material of these bars will lag behind the field, creating a damping torque on the system. PMAC has been shown to reach a steady state oscillation of the spacecraft about the changing local magnetic field lines of ±15° or less[12], which is more than adequate to meet the science requirements of CSSWE. Figure 10 shows how the PMAC system will align CSSWE with earth's local magnetic field throughout an orbit.

In addition, a PMAC system requires no power and very little mass (<50g). In order to justify the performance of PMAC, a simulation must be used. The ADCS team has developed its own PMAC simulation using the MATLAB environment. Within the simulation, a dipole model is used to determine local magnetic field strength and direction throughout the CSSWE nominal orbit. Euler parameters are chosen as attitude coordinates to describe the orientation of the CubeSat over time. Next, the Euler rotational equations of motion are integrated in combination with the Euler parameter kinematic differential equations of motion. The restoring torque of the bar magnet and the damping

torque of the hysteresis rods are modeled as external torques in Euler rotational equations of motion. In order to model the torque supplied by the hysteresis rods, an arc-tangent hysteresis function is used. This function idealizes the physics to supply the induced magnetic flux within the hysteresis rods as a function of the changing magnetic field input. However, due to real-world manufacturing processes and losses, the true behavior of the hysteresis material can be quite different than material predictions. Future work includes a testing device to determine the properties of the flight hysteresis rods, which allows for a more accurate simulation. Figure 11 shows a simulation-generated plot of the angular velocity of the CubeSat over time based on our current PMAC design. As shown, the angular velocity decreases as the CubeSat reaches steady-state. Coupling effects due to spacecraft symmetry are also visible in the figure.

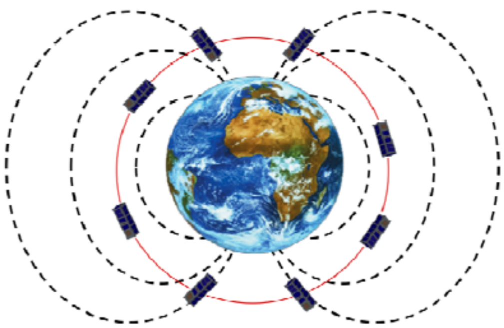

Figure 10: The PMAC system orients the CubeSat to earth magnetic field lines throughout each orbit.

A magnetometer is included on CSSWE to determine the relative angle between REPTile's look direction and the local magnetic field. The HMC5843 3-axis magnetometer has been chosen, with a resolution of 7 milliGauss (the CSSWE requirement is 10 milliGauss). Since the permanent magnet will be fixed with respect to the magnetometer, its field can be subtracted from the measurements. This calibration will be performed prior to flight and its effect can be verified on the ground since earth's magnetic field strength on the ground is of comparable strength to the field-strength at 600 km altitude. The location of the magnetometer, bar magnet, and hysteresis rods within the spacecraft have been set in an effort to minimize the magnetic noise. Also, although the magnetometer is located near several solar panels and the antenna, solar panel wiring will be such that it minimizes external fields (LASP engineers have prior experience with this).

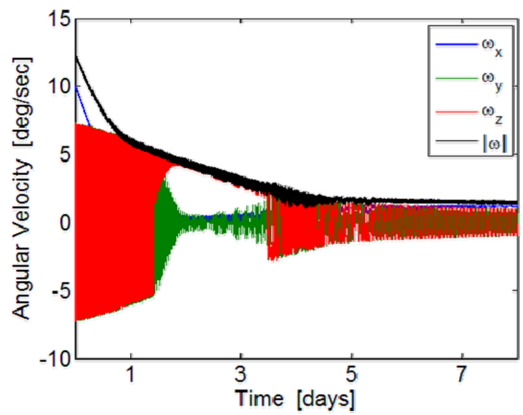

Figure 11: Angular velocity of the CubeSat decreases over time due to the PMAC system. A coupling effect is visible from days 1-4 due to satellite symmetry.

COMMAND AND DATA HANDLING SYSTEM (C&DH)

The Command and Data Handling system is the intelligence unit of the autonomous CubeSat. It controls and communicates with all the subsystems on board collecting the science and housekeeping data. The functional requirements of the C&DH subsystem are:

1. Command REPTile instrument to take science data
2. Receive science data from REPTile instrument
3. Gather housekeeping data from the CubeSat subsystems
4. Perform fault detection and correction (FDC)
5. Send science and housekeeping data to COMM subsystem
6. Receive commands from ground station

Architecture

The C&DH subsystem has 3 major components

1. Motherboard
2. Processor
3. Software/RTOS

The hardware selected for the C&DH subsystem consists of a two-component system offered by Pumpkin Inc. (CubeSat Kit). The pluggable processor is a new architecture developed by Pumpkin which allows the customer to select a processor from a range of choices which can be directly plugged into the motherboard. The Pumpkin CubeSat Kit motherboard provides command and data handling using a pluggable 16-bit MSP430F2618 low-power microcontroller (PPM A3). Given +5 volt input, the flight module provides +5 and +3.3 volts, function timers, launch switches, latch up and over current protection, a Secure Digital (SD) memory card socket for mass storage, an on-board low

dropout regulator and reset (watchdog) supervisor, and supports a wide range of transceivers.

Software

C&DH team has chosen to use the Salvo Pro Real Time Operating System (RTOS) from Pumpkin Inc. to schedule and run tasks on the controller. The Salvo Pro RTOS is a co-operative RTOS designed expressly for very-low-cost embedded systems with severely limited program and data memory. This has been selected after a comprehensive trade study considering the complexity, foot-print etc. There are three major communication protocols being used - SPI, I^2C and AX.25. The C&DH subsystem initially commands the REPTile instrument to start collecting science data. The REPTile instrument sends the science data to the C&DH subsystem via the dedicated I^2C bus (USCI A0/B0). There is a performance specification listed for collecting science data at six second intervals from the REPTile instrument. Hence, a design decision has been taken to use a dedicated I^2C bus to collect science data from REPTile). C&DH then collects the magnetometer data from the ADCS via the shared I^2C bus (USCI A0/B0). After procuring the magnetometer science data, C&DH collects the timestamp data from the RTC present on the Motherboard via a shared I^2C bus (USCIA0/B0). C&DH combines the individual data from these three components into a data sample (30 bytes). It then sends the data samples to the SD card via a dedicated/shared SPI bus (USCI A1/B1) for future retrieval. When requested by COMM, the relevant data samples are collected from the SD Card via the dedicated/shared SPI bus (USCI A1/B1). These relevant samples are then sent to COMM via the dedicated/shared SPI bus (USCI A1/B1).

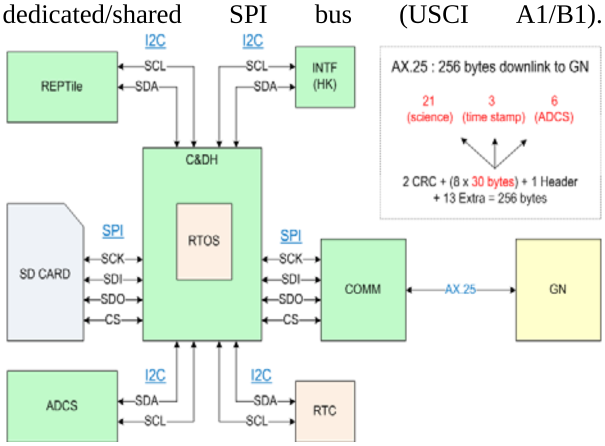

Figure 12: C&DH Block Diagram

Data Packet Structure

Currently, the data packet structure for the science data has been formulated and the data packet structure for the housekeeping data is being developed. Each science data packet consists of 8 data samples, each of size 30 bytes. Each sample consists of 21 bytes of data from REPTile, 6 bytes from the magnetometer (ADCS science data) and 3 bytes from the RTC (Timestamp data). The microprocessor on COMM (MSP430F2618) then groups 8 data samples together along with a 1 byte header, 2 byte CRC and packetizes it into the AX.25 format. There are still 13 extra bytes which could be used in the future for providing additional information about the packet. The COMM subsystem then sends the data packet to the GN.

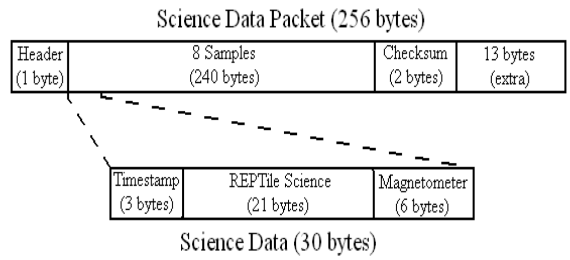

Figure 13: Science Data Packet Structure

Design Flow

Each of the modules which are a part of the science data flow (e.g. collect REPTile science data via the dedicated I^2C bus) is configured as an individual task in Salvo Pro RTOS. Using message queues and binary semaphores, the processor resources are utilized effectively. The previous version of the C&DH architecture comprised of each of the individual protocols configured as individual tasks in Salvo Pro RTOS. However, after some discussion it was established that this would greatly increase the complexity of the software architecture.

C&DH is envisioned as the central hub of the CubeSat, collecting both science and housekeeping data for the entire satellite. This data will be sent as requested by the ground network via COMM. The work completed to date includes: the code development for the I2C, SPI and AX.25 interfaces, the task scheduling in the Salvo Pro RTOS and compatibility with interrupts of the MSP430F2618 processor. Currently, the SD Card operations are being worked on.

COMMUNICATIONS (COMM)

The current design is a half-duplex communication system with two deployable steel-tape monopole antennas connected together with a 180° Hybrid for RF communications, shown in Figure 14. This dual monopole configuration has been tested, and exhibits a gain pattern very close to that of a dipole, shown in Figure 15. This pattern allows communication with the

spacecraft while at most expected attitudes over the ground station.

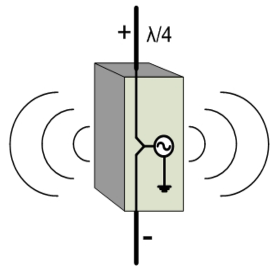

Figure 14: COMM uses dual-monopole steel-tape antennas connected together with a 180° Hybrid.

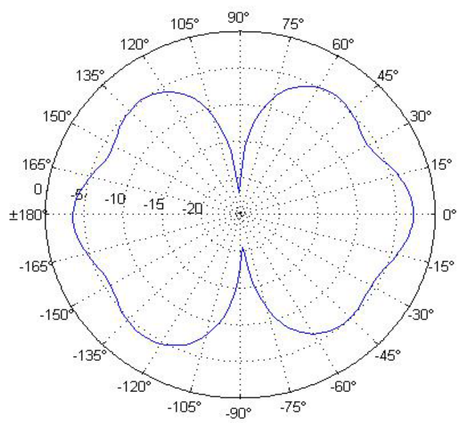

Figure 15: Antenna testing yielded this gain pattern for the dual monopole antennas. The gain pattern is oriented parallel to Figure 14.

The COMM overall block diagram is shown in Figure 16. A GMSK modulation chip has been selected to be the heart of the communications board, the SX1231. This component does much of the transceiver and digital interfacing as well. This GMSK chip has input and output RF stages that are connected to the same antenna via an RF switch that shall be controlled by a microcontroller. The COMM MCU interfaces C&DH with the GMSK modem and sends all data received by C&DH to the GMSK modem to be modulated and transmitted to the GN. It shall also be responsible for translating commands that are sent from the GN and sending them to C&DH via SPI. Under certain events of system failure, the microcontroller will also reset C&DH via a single wire reset line, which can be done autonomously as well as via command from the ground. CSSWE uses a MSP430 microcontroller for COMM and C&DH, which enables a common programming environment and reduces interface complexity.

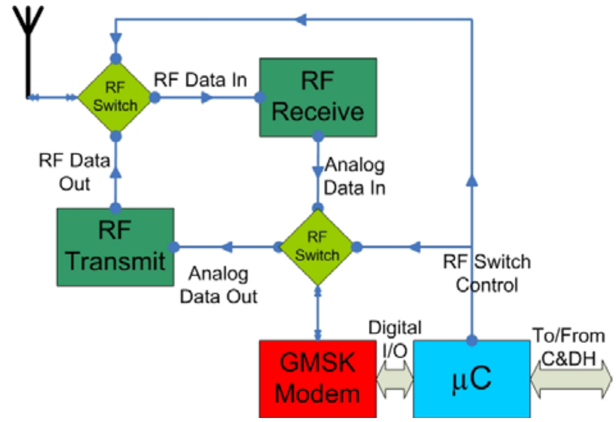

Figure 16: COMM block diagram

The transceiver operates at UHF 433 MHz (amateur band), which allows cooperation with any number of amateur ground stations across the globe. FCC and AMSAT requirements will be met by this system as outlined by the CubeSat Design Specification.[11]

Table 2: Link budget for CSSWE

Symbol	Uplink	Downlink	Units
EIRP	39.51	-4.34	dBW
Propagation Losses	-152.49	-152.49	dB
Receive System Gain	-6.00	18.71	dB
Received Power	-118.98	-138.13	dBW
System Noise Power	-200.83	-200.64	dBW-Hz^{-1}
Carrier to Noise Ratio Density	81.85	62.52	dB-Hz
Minimum Pr/No	55.42	55.42	dB-Hz
Margin	26.43	7.09	dB

shows the link budget for CSSWE. These are computed for a link capacity of 9600 bps, with a bit error rate for both uplink and downlink of 10E-5, GMSK modulation, an orbital altitude of 600km and a ground elevation mask of 15 degrees. The ground station antenna is assumed to be a M2 MCP436CP30 cross polarized 42 element yagi antenna with a gain of 14.15dBdc. An uplink transmitter power of 135W and a downlink power of 1.5W is assumed along with the antenna pattern shown in Figure 15. These results indicate that the link is achievable as designed with

excess margin available. Because of the importance of the communication system in mission success, significant time will be invested in the testing and verification of the operational parameters used to develop the link budget.

EDUCATION

The approach to building the CSSWE CubeSat is to integrate the project into the University of Colorado Department of Aerospace Engineering Science (AES) graduate curriculum. In fall 2008 a hands-on project based learning course entitled "Space Hardware Design" was developed to provide engineering students with an opportunity to learn how to design build and test space hardware. It is envisioned that students will progress through a full spacecraft design process from concept through test and integration in 2-3 years. In 2009 the space hardware design was integrated into a broader graduate projects course. Four to five projects on topics ranging from a mini jet engine development, to the development of autonomous aerial vehicles are offered each year, where CSSWE is one of the ongoing projects. The course is structured where all students, regardless of team affiliation, meet for a weekly 50 minute lecture on topics relevant to systems engineering, project management and teamwork. The remaining two meeting times are lab periods lasting 1 hour and 45 minutes and are used for team meetings and discussion of design issues. During one of these meeting times the students meet with engineers from the Laboratory for Atmospheric and Space Physics (LASP) to receive technical guidance and feedback on their current designs. Each semester the team is required to make two formal presentations. These occur at the mid-point of the semester (after 8 weeks) and at the end of the semester. The end of semester design reviews often last 3-4 hours and are attended by LASP engineering and AES faculty. The function of these reviews is to assess the current maturity of the design and teach the students how to present material during a technical review. Additionally students are required to write and submit a semester end report documenting their contribution to the project. Since the fall 2009 semester more than 30 students have taken the cubesat section of our graduate projects course and currently for the fall semester the class has already reach its maximum enrollment of 20 students. A majority of the students have come to the class from the AES and electrical engineering departments with a couple of students from mechanical engineering and physics. We have found that offering the design and construction of a CubeSat in our graduate program has served to attract excellent new students.

SUMMARY

The Colorado Student Space Weather Experiment is a National Science Foundation funded cubesat project that is being run as a graduate projects course at the University of Colorado. The project will run for 2-3 years taking students from the requirements development process through conceptual, preliminary and critical design onto integration and testing and finally culminating with flight and operations. In addition to meeting our key science requirements of better understanding the spectrum of solar energetic particles associated with solar flares and the energy spectrum of electrons in the earth's radiation belt. The project is directed by faculty in the Department of Aerospace Engineering Sciences in conjunction with support from engineers at the Laboratory for Atmospheric and Space Physics. The project is currently entering the critical design phase and is expected to launch as a secondary payload in 2012.

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