Miniature X-Ray Solar Spectrometer (MinXSS)
A Science-Oriented, University 3U CubeSat

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ABSTRACT
The Miniature X-ray Solar Spectrometer (MinXSS) 3U CubeSat is scheduled to launch to the International Space Station (ISS) on ORB-4 in November 2015. MinXSS was designed and developed as part of the Aerospace Engineering Sciences (AES) graduate projects course at the University of Colorado in Boulder (CU) with significant facilities and professional support from the Laboratory for Atmospheric and Space Physics (LASP). Some of the spacecraft design is heritage from the highly successful Colorado Student Space Weather Experiment (CSSWE) CubeSat, which was the result of the same AES/LASP collaboration. The project course was initially supported by AES and NSF, and MinXSS flight has been funded as a science mission by the NASA Heliophysics Division.

This paper will provide an overview of the MinXSS science of observing the highly energetic solar soft X-ray (SXR) radiation, the educational program of involving students in design, building, and testing a CubeSat, and some lessons learned.

MISSION OVERVIEW
The Miniature X-Ray Solar Spectrometer (MinXSS) is a 3U CubeSat that began development as an aerospace student project at the University of Colorado Boulder (CU) and the Laboratory for Atmospheric and Space Physics (LASP) in August 2011. The primary objective of the science-oriented MinXSS CubeSat is to better understand the energy distribution of solar soft X-ray (SXR) emission and its impact on Earth’s ionosphere, thermosphere, and mesosphere (ITM). With NSF support in 2013 and subsequent NASA funding in 2014–2016, three MinXSS units have been fabricated (Figure 1): a prototype and two flight models. The prototype MinXSS has been valuable for early testing and fit checks, and as extra unit for developing flight software in parallel with other build activities. MinXSS flight model 1 (FM-1) is ready for launch and is manifested on the fourth International Space Station (ISS) resupply mission by Orbital ATK (ORB-4), to be launched on an Atlas V on 19 November 2015. MinXSS FM-1 will be deployed from a NanoRacks CubeSat Deployer on the ISS in January 2016, where it will have an expected 5–12 month orbital lifetime, dependent on atmospheric conditions. MinXSS FM-2 is being planned for a higher altitude, longer mission in a sun-synchronous polar orbit (SSPO) via a launch on the Skybox Minotaur C launch in 2016. This section provides an overview of the science objectives, the history of the project, and the spacecraft subsystems.
Science Objectives - Overview

There is a rich history of solar SXR spectral observations over the past three decades, but with a significant gap of spectrally resolved measurements in the 0.4–6 nm range.\(^1\) There were many new discoveries about solar flares during the 1980s using solar SXR spectral measurements from the DoD P78-1, NASA Solar Maximum Mission (SMM), and JAXA Hinotori satellites. For example, Doschek provides results about flare temperatures, electron densities, and elemental abundances for some flares during these missions.\(^2\) A review of flare observations from Yohkoh and the Compton Gamma Ray Observatory (CGRO), for the hard (higher energy) X-ray (HXR) range, is provided by Sterling et al.\(^3\) These earlier missions laid a solid foundation for studies of flare physics and flare spectral variability that the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the Solar Dynamics Observatory (SDO) continue today for the HXR and EUV ranges, respectively.\(^4,5\) With solar flare spectral variability expected to peak near 2 nm, in a range not currently observed by any spectrometer, MinXSS measurements of the solar SXR irradiance will provide a more complete understanding of flare variability in conjunction with measurements from RHESSI and SDO EUV Variability Experiment (EVE).\(^6,7\)

There are also nearly four decades of broadband (5-10 nm wide) SXR measurements that do not provide spectrally resolved measurements. The very limited spectral information from these broadband measurements cannot quantify the specific spectral energy distribution, nor directly quantify the varying contributions of emission lines (bound-bound) amongst the thermal radiative recombination (free-bound) and thermal and non-thermal bremsstrahlung (free-free) continua. These broadband measurements include, among others, the two GOES X-Ray Sensor (XRS) channels covering a combined band of 1.6–25 keV (0.05–0.8 nm) and the even broader band of 0.2–12 keV (0.1–7 nm) from several missions, including the Yohkoh Soft X-ray Telescope (SXT, 1991–2001), Student Nitric Oxide Experiment (SNOE, 1998–2002), Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED, 2002–present), the Solar Radiation and Climate Experiment (SORCE, 2003–present), and SDO (2010–present).\(^8,9,10,11,12\) Broadband measurements of solar SXRs have helped to resolve an outstanding difference between ionospheric models and measurements, such as the electron density from the Haystack Observatory incoherent scatter radar at
Millstone Hill. In particular, the SNOE solar measurements were able to resolve the factor-of-4 difference between models and measurements because the SNOE data indicated much more SXR irradiance than had been previously thought.13 Additional broadband SXR measurements have been made since then; however, differences still remain in understanding solar SXR spectral distribution and atmospheric photoelectron flux. While smaller, these discrepancies are still as large as a factor of 2 at some wavelengths, as shown in Figure 2; the lack of spectral resolution in the SXR range is thought to be the culprit for most of these disagreements. For example, Peterson et al. show that discrepancy between photoelectron measurements and models were significantly improved with new EUV spectral measurements down to 6 nm, and we anticipate further improvement with new solar SXR spectral measurements and atmospheric modeling with data from MinXSS due to its ability to measure all wavelengths in its spectral range simultaneously and with the relatively high spectral resolution of 0.15 keV FWHM.14

**Science Objectives – Solar Flare Studies**

Spectral models of the solar irradiance (e.g., CHIANTI) are needed in order to convert spectrally-integrated broadband measurements into irradiance units.15,16 Detailed modeling to estimate the SXR spectrum during a flare in April 2002 using a set of broadband measurements from the TIMED Solar EUV Experiment (SEE) was performed by Rodgers et al.6 The CHIANTI spectral model is part of their analysis and is also routinely used for processing these broadband measurements. e.g.-17 While the CHIANTI spectra are scaled to match the broadband SXR irradiance in data processing, there are significant differences for individual emissions lines between the CHIANTI model and observations, often more than a factor of two.18,19 Furthermore, there are concerns that CHIANTI could be missing many of the very hot coronal emissions lines, especially in the SXR range where there are so few spectral measurements between 0.5 and 6 nm. Additionally, there are factor of 2 differences when comparing the irradiance results from different broadband instruments, which are worst during times of higher solar activity (Figure 2). These discrepancies can be partially explained by wavelength-dependent instrument calibrations, but the greater contribution is likely the lack of knowledge of how this dynamical part of the solar spectrum changes as a function of wavelength and time.

The MinXSS spectrometer, an Amptek X123-SDD, flew on the SDO/EVE calibration rocket payload in June 2012, and that measurement had a difference of almost a factor of 8 below 2 nm as compared to the CHIANTI model prediction based on SORCE XPS broadband measurements.20 This rocket result was a surprise considering that the SORCE-based CHIANTI model prediction agreed with SDO/EVE measurements down to 6 nm. Improvement of models of the solar SXR spectra, which is only possible with calibrated spectral measurements of the SXR emission, is critical to properly interpret these broadband measurements. Our goal with MinXSS observations is to reduce these SXR spectral differences from factors of 2 or more down to less than 30%. In addition, MinXSS will measure solar SXR spectra with higher spectral resolution of 0.15 keV FWHM, as compared to the 0.6 keV FWHM resolution of the most recent analogous instrument, MESSENGER SAX.21 The MinXSS measurements will enable improvements to solar spectral models, such as CHIANTI and the Flare Irradiance Spectral Model (FISM)22,23 By using MinXSS to improve the FISM predictions in the SXR range, atmospheric studies over the past 30 years will be possible, such as those for the well-studied Halloween 2003 storm period, as well as future space weather events after the MinXSS mission is completed. Getting this spectral distribution of solar flare energy in the SXR range is critical as a driver for atmospheric variations, and will be discussed in another section.

![Figure 2: Solar 0.1-7 nm irradiance currently measured by broadband SXR photometers onboard NASA’s SORCE and SDO satellites.](image-url)

The MinXSS data will also help improve understanding of the physics of solar flares themselves. The 0.5–9 keV (0.13–2.4 nm) range observed by MinXSS is rich with high-temperature spectral lines from coronal plasma with temperatures from ~5 to 50 million K, which are greatly enhanced during even small solar flares. MinXSS will also observe the underlying free-free and free-bound continua, extending out to 20–30 keV, which can provide an independent diagnostic of the emitting plasma temperatures. Understanding how solar flares heat plasma, especially up to many tens of
million K, is a pressing question in solar physics, and the MinXSS observations will provide the best spectral measurements in this energy range to date, e.g., 19,24,25

Observing the variations of spectral lines in comparison to the continuum will also provide insight into coronal elemental abundances, particularly for Mg, Si, Fe, S, and Ar, to help measure abundances and to understand how they may vary with solar activity and during flares.

Science Objectives – Quiescent-Sun Studies

Examples of data analysis and spectral modeling for two quiescent (non-flaring) solar measurements made with the X123 aboard the SDO EVE calibration rocket flights in 2012 and 2013 are provided by Caspi et al.20 One of the tantalizing results from these two 5-minute observations is that the coronal abundance of certain elements is different for the quieter SXR spectrum on June 23, 2012 than the more active (but not flaring) Sun on October 21, 2013. These abundance differences suggest that different heating mechanisms occur in the quiet network versus active regions, and support the concept that numerous small impulsive events ("nanoflares") could be the source of the active region heating, e.g., 6,26 Identifying the mechanism responsible for heating the quiet Sun corona to millions of degrees, while the photosphere below it is only 6000 K, remains one of the fundamental outstanding problems in solar physics.27 We anticipate that 1–3 months of MinXSS measurements of the solar SXR spectrum will provide adequate data on active region evolution and several flares to more fully address these questions on nanoflare heating. The SXR variability is about a factor of 100–1000 over the solar cycle and can be as much as a factor of 10,000 for the largest X-class flares; MinXSS will be able to observe not only small (A- or B-class flares), but also emission from the truly quiet Sun, as well.

Science Objectives – Improvements to Earth Atmospheric Models

Energy from SXR radiation is deposited mostly in the ionospheric E-region, from ~80 to ~150 km, but the altitude is strongly dependent on the incident solar SXR spectrum. This wavelength dependence is due to the steep slope and structure of the photoionization cross sections of atmospheric constituents in this wavelength range. The main reason that Earth’s atmospheric cross section changes so dramatically in this range is due to the K-edges of O at 0.53 keV (2.3 nm) and of N at 0.4 keV (3.1 nm). Figure 3 shows two different solar SXR spectra (top) and the result of their absorption in Earth’s atmosphere (bottom). Although the two solar spectra are normalized to have the same 0.1–7 nm integrated irradiance value, their peak energy deposition near the Earth’s mesopause has a separation of about 5 km. This separation is considered significant because it is approximately equal to the scale height at 100 km, it is critical to E-region electrodynamic interactions, and the mesopause (the coldest region of the atmosphere) is a critical transition between the middle and upper atmosphere.

Figure 3: (top) Two examples of CHIANTI model solar spectra at 0.01 nm resolution, scaled to have identical 0.1–7 nm integrated energy flux: a Sun with bright but non-flaring active regions (green), and a solar flare (red). (bottom) Earth atmospheric absorption profiles resulting from the two incident solar spectra in the top plot.

The MinXSS solar SXR spectra are also important to address outstanding issues concerning E-region conductance that has an enormous effect on global electrodynamic interactions and the F-region, especially through the influence of the equatorial electrojet. One of the issues concerns the inability of global general circulation models or detailed process models to produce enough ionization to agree with the E-region peak densities from measurements or well-established empirical models. There appears to be insufficient energy in the solar spectra used as model input, either
in the SXR region (especially ~1–3 nm) or at H Lyman-β 102.6 nm. The latter has been well quantified by TIMED and rocket measurements. Thus, the focus on the solar SXR spectrum may reveal this missing energy for the E-region. The models could more accurately describe important phenomena such as the magnitude and morphology of the equatorial ionization anomalies, pre-reversal enhancement of the vertical electric field, and the effects of tidal perturbations on the F-region.

**Project History and the Near Future**

The MinXSS project began as a graduate student project in the Aerospace Engineering Sciences (AES) department at CU and ran through the Spring 2014 semester, with an average of 11 graduate students each semester. The AES department supported the first year of the project, which focused on development of the CubeSat Card Cage design and assembly (see later section). The second year was supported by the National Science Foundation (NSF), which enabled the design and manufacture of the first flight prototype (see Figure 1 left), which included the structure, command and data handling (CDH) custom board, electrical power system (EPS) custom board, custom motherboard, custom battery pack, and plastic 3D printed prototypes of the secondary instrument housing and antenna deployment module. NASA awarded full funding in the project’s third year to support flight build, integration, environmental testing, mission operations, data analysis, and public data distribution.

At the present time, FM-1 has completed environmental testing and is ready for delivery and launch later in 2015, with deployment expected in early 2016. FM-2 has been built and integrated and is now ready for environmental testing in late 2015 and launch in mid-2016. Mason et al. (2015) provides additional details about the launch vehicles for both FMs and ISS deployment for FM-1.1

**Subsystems**

MinXSS has all the standard subsystems for a satellite, except propulsion. Figure 4 shows a high-level electrical block diagram for MinXSS. A mechanical block diagram can be found in Mason et al. (2015).1 The purple boxes in the upper right of Figure 4 show the Remove Before Flight (RBF) and three rail switches that disconnect the battery from the system. This number of switches was required by the NanoRacks deployer to comply with ISS human safety standards.

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**Figure 4: MinXSS electrical block diagram.**
A resource breakdown and outline of each subsystem can be found in Mason et al (2015). To summarize each: the attitude and determination control system (ADCS) is a Blue Canyon Technologies (BCT) XACT unit; the EPS, CDH, battery board, motherboard, antenna, and SPS & XS instruments were custom designed and built at CU and LASP; the radio is a AstroDev Li-1 radio on a custom PCB; the solar cells are Azur Space 30% efficient, triple-junction GaAs; and the primary science instrument is an Amptek X123-SDD.

**ADVANCING CUBESAT TECHNOLOGIES AND LESSONS LEARNED**

This section discusses lessons learned that were incorporated in MinXSS and new lessons from the development. It also makes calls to the community that will aid in future CubeSat development efforts.

**CubeSat Card Cage**

Experience with the PC104 PCB interface on the Colorado Student Space Weather Experiment (CSSWE) CubeSat led us away from the card stack design due to the difficulty in debugging boards once integrated. Instead, our CubeSat Card Cage design uses a motherboard/daughterboard architecture that allows any individual card to be easily removed, and an extender board optionally inserted to have access to the daughterboard for probing while still electrically connected (Figure 5). Additionally, the standard electrical interface allows boards to be swapped to any position. MinXSS utilizes a DIN 48-pin connector for the daughterboard-motherboard interface. This relatively large connector was chosen for ease of soldering for new engineering students and because it easily satisfied the requirements on the number of necessary pins and mechanical dimensions. In the future, a higher density connector with potentially more pins could be chosen to provide a lower mass and lower volume solution while still providing the flexibility of the card cage architecture.

**3D Printed Parts**

MinXSS used 3D printed parts for both prototyping and flight components. For prototyping, the SPS & XS housing was 3D printed in plastic twice as the design iterated, and the solar array hinges were printed in plastic once. This was done using CU’s Objet 30 printer with VeroWhitePlus plastic. For flight, these same components were 3D printed in metal using direct metal laser sintering at GPI Prototype. The SPS & XS housing is aluminum with a shot blasted finish. A minimal amount of sanding was required for these parts because the requirements were looser and the finish was slightly better than SPS & XS. The better finish was likely due to the hinges being a simpler part that required no filler material during the 3D print (sintering) process.

As plastic 3D printers become more pervasive, affordable, and precise, the draw toward using the resultant parts for flight is becoming stronger. A major risk that must be addressed is the unknown properties of these materials, particularly in their response to vacuum and UV exposure. We would like to see an open database where specifications based on test results for common 3D print materials, such as ABS and PLA, could be accessed.

**Figure 5: Prototype CubeSat Card Cage design with Amptek X123-SDD on top.**

**Simplification of Solar Panel Fabrication Process**

CSSWE used epoxy (Arathane 5753) on the back of solar cells to adhere them to the solar panel PCBs. This technique is typical but requires significant assembly and curing time. MinXSS used double-sided Kapton tape with acrylic adhesive to adhere solar cells to the
PCBs. We used a specialized rubber vacuum sealer to apply pressure to the cells uniformly and meet the manufacturer’s recommended application pressure. This reduced the time to produce a solar panel from three days to one day. To get electrical conductivity from the back of the solar cell to the PCB, we applied silver epoxy in large vias behind each cell. We also tested a new-to-market tape, called Z-Axis tape by 3M, which is electrically conductive between the adhesive and back sides and could save the extra step of applying the silver epoxy or soldering/welding on tabs. We decided to use Kapton tape for flight because the Z-Axis tape adhesive was not rated for as wide a temperature range as the Kapton acrylic adhesive, there was concern that the Z-Axis tape could not sustain the high current of the solar cells for as long as solder or silver epoxy could, and we did not understand the Z-Axis tape thermal conductivity properties as this information was not available in the Z-tape specification sheet.

In the future, we would like to see solar cell manufacturers adopt a standard form factor compatible with CubeSats. MinXSS uses 40 mm × 80 mm cells from Azur Space, which are a great fit within the rail boundaries of CubeSats (maximum of 83 mm wide and 340.5 mm long for 3U CubeSat). The 80 mm width for cells provides 1.5 mm margin on each side from the rails. If the spacing between cells could be reduced to 4.5 mm or less, then there could be 8 Azur Space solar cells instead of 7 on a 3U panel. Alternatively, if the height of the cells were changed to be 50 mm instead of 40 mm, then they would be more modular for fitting one solar cell per 0.5U of the panel length. With six 50 mm x 80 mm cells instead of seven 40 mm x 80 mm cells, there could be 7% more power per 3U panel.

**Pseudo-Peak Power Tracking**

We modified the DET EPS design that was inherited from the CSSWE CubeSat to include an additional specially selected resistor to create a pseudo-peak power tracking (PPPT) system. The extra resistor was chosen to prevent a rapid voltage drop from the solar cells when the battery attempts to draw a large current, namely when the battery state of charge is relatively low right as the spacecraft exits the orbit eclipse.

In the CSSWE and MinXSS EPS design, the output of the solar panels power 8.6 V regulators that then provide regulated 8.5 V power directly to the battery and system. In this DET design, the batteries will charge up to 8.5 V, and there are no supporting electronics required to control the battery charging process. In reality, this simple approach only provides about 50% of the power intended from the solar panels when the battery capacity is low. In particular, when the battery needs more power input (high current) for charging, the high current draw from the solar cells results in much lower voltage, following the standard solar cell current-voltage (I-V) curve. When the solar panel output voltage goes below the minimum input voltage level of the 8.6 V regulator, the regulator turns off. Consequently, the current drops and the solar panel output voltage increases, and the 8.6 V regulator turns back on. This results in a high-frequency on-off regulator oscillation that had the regulator oscillation signal for only about 50% of the time during the early part of the orbit dayside during mission simulations. The MinXSS solar panels were designed for 80% of peak efficiency at EOL, but the 50% decrease in power was an unacceptable power loss for the nominal power budget.

The solution for MinXSS, without having to redesign or rebuild the EPS board, was to replace the sense resistor on the output of the solar panel regulator with a larger resistance so that the effective current draw out of the solar panel would be limited and thus would not cause the regulator to turn off. We refer to this current-limiting resistor for the solar panels as pseudo-peak power tracking (PPPT). Figure 6 shows a simplified version of the PPPT circuit for the MinXSS EPS.

![Figure 6: A simplified circuit diagram of PPPT used for the MinXSS EPS.](image)

The value for this current-limiting resistor was estimated for the MinXSS power configuration using Eq. 1. The first term on the right-hand side of Eq. 1 is the current for the spacecraft load, and the second term is the current for charging the battery. The spacecraft load is assumed constant, but the battery charging current starts off high when the battery voltage is low and then ramps down to zero when the battery voltage is the same as the regulator voltage downstream of the current limiting resistor. The ideal value for the current-limiting resistor, $R_{CL}$, is such that it limits the current out of the regulator, $I_{R_{Reg}}$, to be less than the maximum current, $I_{max}$, possible from the regulator (at the peak power part of the solar panel I-V curve) and when the battery voltage, $V_{Bat}$, is at the lowest allowed level. For the MinXSS design and configuration, the regulator voltage, $V_{Reg}$, is 8.5 V, the worst-case system load (largest power) has 7.0 Ω for $R_{SC}$, a battery impedance...
of 0.125 Ω, and a value of 2.8 A for $I_{\text{max}}$. The goal for MinXSS was to keep the battery voltage above 7.1 V at all times, so an $R_{\text{CL}}$ of 0.25 Ω is the desired value for the MinXSS configuration to satisfy Eq. 1. That is, with this value of $R_{\text{CL}}$, $I_{\text{Reg}}$ equals $I_{\text{max}}$ when $V_{\text{Batt}}$ equals 7.1 V.

$$I_{\text{Reg}} = \frac{V_{\text{Reg}} - I_{\text{max}} R_{\text{CL}}}{R_{\text{S/C}}} + \frac{V_{\text{Reg}} - I_{\text{max}} R_{\text{CL}} - V_{\text{Batt}}}{R_{\text{CL}} + R_{\text{Batt}}}$$  \hspace{1cm} (1)

After the current-limiting resistor was installed into the EPS, additional mission simulations were run. We verified that the prediction of the regulator current, $I_{\text{Reg}}$, and the measured battery voltage agreed with the measured regulator current.

One disadvantage to the PPPT implementation is that there is additional heating of the EPS board because of the larger resistance; however, this extra heating peaks right after exiting eclipse, the precise time when temperatures are cooler and heating is desired anyway. For example, the power loss (heating) in the PPPT current-limiting resistor is estimated to be 2.6 W when the battery voltage is at its lowest value of 7.1 V, decreasing to 0.93 W when the battery voltage is at 7.5 V, and reduces to less than 0.1 W once the battery voltage is above 8.0 V. The primary caveat in the PPPT design is that resistor tuning must be done a priori, and is fixed, whereas maximum PPT (MPPT) systems can tune resistance in real time to maintain the maximum power point on the solar cell I-V curve. The trade studies performed for CSSWE and MinXSS resulted in the selection of a custom DET EPS due to the simplicity of design. Both teams were unaware of the consequential loss of power generation at the time of the original designs. The advantage of the PPPT circuit is that it is only minimally more complex than DET, adding little risk for a large benefit.

In the future, we would like to see a standard MPPT IC for interfacing to common CubeSat battery packs (e.g., 8.4 V Li-polymer battery packs). We found it difficult to identify a commercial MPPT IC or proven MPPT circuit that could be integrated with our system. We purchased the most promising MPPT IC, a Linear Technology LT3652, and spent significant time attempting to integrate it with the MinXSS EPS, but its intended use prevented proper functioning for our solar panel and battery configuration.

**Importance of Flight-like Testing**

Various tests were performed on MinXSS that were geared toward simulating the orbital environment and flight-like operations. These included low-external-torque tests of the ADCS, thermal vacuum with a long-duration mission simulation, early-orbit end-to-end communication testing performed several miles away from the ground station, and detailed battery characterization of the actual batteries to be flown.

Using a custom-built air-bearing table, we tested the functionality and performance of the ADCS. This test simulated an orbital environment with reduced external torques present. Through this testing, we discovered that an operational amplifier (op-amp) was preventing the XACT coarse sun sensor from being properly read by its internal flight software, and this op-amp was replaced to resolve this issue. It is unlikely this would have been discovered otherwise, and may have resulted in the spacecraft not being able to quickly find or accurately track the Sun on orbit. Significant effort in mission operations may have been able to salvage the mission in that situation, but only minor effort was required to replace the offending op-amp. Air-bearing testing requires very careful balancing of the system and as much reduction of external torques as possible; e.g., even air flow from building ventilation could limit the tracking duration while operating on the air-bearing table. It also requires the computation of moments-of-inertia specific to the air-bearing-CubeSat system to be provided to the ADCS for appropriate control to be implemented. Without such an update to the ADCS software, the ADCS response is too sluggish (slow) to confirm that the ADCS is tracking as expected.

Thermal vacuum tests are irreplaceable for determining if the CubeSat can function in vacuum and for measuring performance near the operational limits of components. Through such testing of MinXSS, we discovered a short in a battery heater that reset the entire system every few seconds, which only manifested under vacuum. This was caused by the battery expansion, which created an unintended electrical connection between the two nodes of the heater. Typically, CubeSats are only required to bake out, not perform a functional thermal vacuum test, but we highly recommend this test as a process to increase the success rate of CubeSats.

A 100-hour mission simulation test was performed on MinXSS during four of the eight hot-cold cycles of the thermal vacuum testing. A solar array simulator, with an I-V curve programmed to model the Azur Space solar cells used on MinXSS, was jumpered into the MinXSS EPS board. The jumper bypassed the two deployable solar panels. The output of the solar array simulator was programatically cycled in intervals corresponding to ISS orbit insolation/eclipse periods at three different $\beta$ angles. The total orbit period was 93 minutes and the three eclipse periods were 28 minutes (average $\beta$), 38 minutes ($\beta = 0^\circ$), and 0 minutes ($\beta >$...
We collected power performance data of the entire system throughout each of these scenarios, and verified that the PPPT maintained a power positive state through many orbits. Additionally, this test was used to verify the functionality of a flight-software commandable flag to disable power to the X123 during eclipse periods. This option was introduced into the flight software early in the project in anticipation of a marginal power balance. The X123 was chosen for power cycling because it is the largest consumer of power and because the primary science target – the Sun – is not visible in eclipse. However, this is not the default state in the mission design as it introduces excessive power cycling on the primary science instrument; nominal operations leave the X123 powered on during the entire orbit. As the spacecraft performance degrades on orbit (e.g., solar cell efficiency loss), it may become necessary to enable the X123-eclipse-power-cycling flag. Finally, the 100-hour mission simulation test included periodic stored-data downlinking with durations equivalent to the ground station contacts expected on orbit. The 100-hour mission simulation test was the most flight-like testing possible with the facilities available, and greatly increased confidence in and understanding of the system as it will behave on orbit. It also ensured that the flight electronics are likely past the “infant mortality” phase.

End-to-end testing was also performed on MinXSS to verify functionality of the full communication pipeline. The spacecraft was taken several miles away to a position in the line-of-sight of the ground station, and early-orbit commissioning tests performed. This boosted confidence in several areas: that we would meet the NanoRacks requirement of not deploying the MinXSS antenna or solar arrays in the first 30 minutes after deployment from the ISS, that those deployments would be successful, that communications could be established after antenna deployment, and that our ground software commissioning scripts could autonomously perform telemetry verification and commanding.

Significant battery testing was performed to comply with requirements flowed down from NASA Johnson Space Center through NanoRacks to all CubeSats going to the ISS. These requirements are in place to protect astronauts on the ISS and far exceed the standard CubeSat requirements in the Cal Poly CubeSat Design Specification. Nevertheless, we recommend that all CubeSats perform several of these tests, if only to better understand the actual batteries to be flown, i.e., not just batteries from the same lot or of the same type. We found the following to be the most useful tests: visual inspection for dents or leaks, measuring the open circuit voltage of the fully configured battery pack, recording voltage, current, and temperature through three charge/discharge cycles, measuring the voltages at which overcharge and over-discharge protection activated and deactivated, and measuring mass before and after undergoing vacuum. Given availability of the equipment to perform these tests and measurements, it took approximately two weeks to complete this testing for each battery pack. Much of that time was dedicated to setup, waiting for charge cycles to complete, and interpretation of the results. Additional tests were required for astronaut safety on the ISS, but we would consider them to be extraneous for non-ISS CubeSat missions. These include measuring of the physical dimensions of each battery, measuring the closed circuit voltage of the fully configured battery pack, measuring the time to trigger short-circuit protection and maintaining the short for three hours to verify the protection remains enabled, and doing a dedicated vibration test at five frequencies and strengths up to 9.65 g_max on all three axes, with voltage measurements between each axis. These additional tests took several weeks of additional time and planning, particularly in the design, manufacturing, and modification of components to support vibration testing.

**Importance of a Second CubeSat Unit**

The fabrication of two identical sets of hardware in parallel is much less expensive than the same development in series, particularly if the start of the development for the second set is delayed by months or years. Small projects tend to have less stringent requirements on documentation, so details can be forgotten and lost in the time between two sets of flight hardware developed in series. Having two sets of hardware enables the development and testing of flight software while other activities proceed in parallel. Importantly, parallel development also enables the replacement of a subsystem if a problem is found, which is critical when schedules are tight. This was the case for MinXSS when the battery heater short was discovered in FM-1 at the initial pump-down for its thermal vacuum test. We were delayed half a day to swap the battery pack out with FM-2, which did not have the same issue, as compared to the weeks of delay that would have been introduced if an entirely new battery pack had to be assembled and tested. Finally, having a second flight unit allows for debugging of hardware and software after delivery and launch of the first flight unit.

**Low-cost Mitigation of Radiation Issues for Electronics**

The CubeSats developed at CU and LASP have generally used industrial-grade (automobile) electronic parts because those parts have wider operating
temperature ranges. Typically, the automobile-grade ICs cost $10 as compared to $2 for standard commercial ICs, but this additional cost is outweighed by the significant benefits of the higher-grade components. For example, the number of uncorrected SD card write cycles can be improved by a factor of 10–100, and the operational temperature range expanded by purchasing a $70 4 GB hardened SD-card instead of a $4 standard SD-card. The total cost impact on MinXSS for these industrial-grade electronics parts is only a few thousand dollars, a small fraction of the total budget, but it significantly improves the potential for a longer mission life. While our intention was to have electronics that could operate over a wider temperature range, automobile-grade parts may also help with radiation tolerance of the electronics. Two MinXSS prototype CDH boards were radiation tested, one to 10 kRad and another to 25 kRad; both boards survived. It is not clear if industrial-grade parts made a difference or not for passing the harder radiation test; nonetheless, it is only a small cost increment to use the higher-grade parts.

SUMMARY AND CONCLUSIONS

MinXSS is a 3U CubeSat developed at CU and LASP with two flight models: one to be launched in late 2015 and the second to launch in mid-2016. This development leveraged heritage from the highly successful CubeSat, CSSWE, which was also developed at CU and LASP. The primary science objective of MinXSS is to fill a critical spectral gap in solar measurements currently made by large satellite missions at 1/100th their typical cost. All standard satellite subsystems are present in MinXSS, except propulsion, packaged in a volume that can fit in a breadbox. Many of these subsystems were custom developed by CU and LASP (e.g., CDH, EPS, SPS & XS, structure), primarily by graduate students with professional mentorship, and other subsystems were purchased from commercial vendors (e.g., flight radio, ADCS, primary science instrument).

In the future, 6U, 12U, and 27U CubeSat standards will open up even more science capabilities by allowing for larger and more sophisticated instruments. Standardized buses that can be commercially procured are now becoming available. Typically 1–2U in size, this leaves ample mass and volume to be used for the science payload. As X-band transmitters and LEO-accessible global network communications, such as GlobalStar, become available in the near-term, it will also be possible to expand data downlink capabilities. This increase in data volume is a critical need for science that involves imaging, as even a single image from a small camera would take hours to downlink at the CSSWE / MinXSS rate of 9600 bps. We note that active pixel CMOS array detectors provide one alternative mitigation strategy for this, if the entire image does not need to be downlinked. Finally, CubeSats will enable science that was not conceivable with large, monolithic spacecraft. For the same cost as a NASA Small Explorer, a constellation of dozens of CubeSats could be put into orbit to obtain simultaneous measurements over a wide spatial distribution. These novel data will enable new scientific observational analyses and provide new constraints to physical and empirical models.

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