MinXSS

Miniature X-ray Solar Spectrometer (MinXSS) CubeSat Mission

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Performance Period: March 2014 – April 2016

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MinXSS CubeSat Mission Summary

***Objectives*.** The primary objective of the Miniature X-ray Solar Spectrometer (MinXSS) CubeSat is to better understand the energy distribution of solar flare soft X-ray (SXR) emissions and its impact on Earth's ionosphere, thermosphere, and mesosphere (ITM). The peak solar energy in the SXR is expected to be emitted near 2 nm, yet we have limited spectral measurements near that wavelength to verify this expectation. Energy from SXR radiation is deposited mostly in the ionospheric E-region, from ~80 to ~150 km, but the precise altitude is strongly dependent on the SXR spectrum because of the steep slope and structure of the photoionization cross sections of atmospheric gases in this wavelength range. Despite many decades of solar SXR observations, almost all have been broadband low-resolution measurements with insufficient spectral resolution to fully understand the varying contributions of emission lines amongst the underlying thermal and non-thermal continua. Consequently, these broadband measurements do not constrain where in Earth's atmosphere the solar SXR energy is deposited; this is the driving motivation for MinXSS to measure the solar SXR spectrum. Furthermore, the interpretation of broadband measurements requires the use of solar spectral models, even to obtain the correct total energy flux. Significant differences are seen between the broadband measurements, sometimes more than a factor of two, apparently due to the lack of precise knowledge of the distribution in the SXR spectrum. The importance of the MinXSS mission is (1) providing new spectral observations of the solar SXR near the maximum of solar cycle 24, (2) improving the understanding of how highly variable solar X-rays affect the ITM, and (3) advancing the knowledge of flare energetics in the SXR.

A secondary objective of MinXSS is to train students as the next generation Science, Technology, Engineering, and Mathematics (STEM) workforce. The students will learn – through formal university classes and with hands-on experience – about scientific instrumentation, satellite technology, and science data analysis and modeling techniques. The MinXSS project began as a graduate student project two years ago in the Space Hardware Design (CubeSat) course developed in the Aerospace Engineering Sciences (AES) department of the University of Colorado (CU) in Boulder.

***Methodology*.** MinXSS is a solar-oriented, 3-axis-controlled CubeSat to observe the solar SXR spectrum between 0.04 and 3 nm. The X-ray spectrometer on MinXSS has a spectral resolution that is almost constant in energy, better than 0.15 keV full width half maximum (FWHM). This X-ray spectrometer flew successfully on a NASA sounding rocket payload in June 2012 and is therefore at TRL 7. The MinXSS students, with professional mentors, have already developed and fabricated the majority of the MinXSS spacecraft using internal CU support for student projects and benefit from strong heritage with the Colorado Student Space Weather Experiment (CSSWE) CubeSat that has had a very successful mission in 2012-2013. The MinXSS project is ready to begin environmental tests next spring and could be ready for launch in November 2014. The only major subsystem to be purchased is the Attitude Determination and Control System (ADCS) from Blue Canyon Technologies (BCT); the BCT 0.5-Unit ADCS has been developed for the Air Force and is available for purchase this fall. The proposed MinXSS work entails mostly mission operations and data analysis. CU's CubeSat course is the primary conduit for student recruitment and training on this CubeSat mission. Modeling with the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM), using these solar SXR measurements as input, will investigate the varying solar energy deposition and dynamical effects in the ITM. The new solar SXR spectral measurements will be used to improve upon the empirical Flare Irradiance Spectral Model (FISM) that is used for a variety of space weather research applications.

1. Science Objectives, Measurements, Importance, and Relevance

1.1. Science Objectives

The science objective of the Miniature X-ray Solar Spectrometer (MinXSS, pronounced "minks") CubeSat is to better understand the solar irradiance energy distribution of solar flare soft X-ray (SXR) emission and its impact on Earth's ionosphere, thermosphere, and mesosphere (ITM). 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 SXR spectrum. This wavelength dependence is due to the steep slope and structure of the photoionization cross sections of atmospheric gases 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 1 shows two different solar SXR spectra. Although they have the same 0.1-7 nm integrated irradiance values, their peak energy deposition near the mesopause has a separation of about 5 km. This separation is considered significant because it is about one scale height near 100 km, it is critical to E-region electrodynamics, and the mesopause, the coldest region of the atmosphere, is a critical transition between the middle and upper atmosphere.

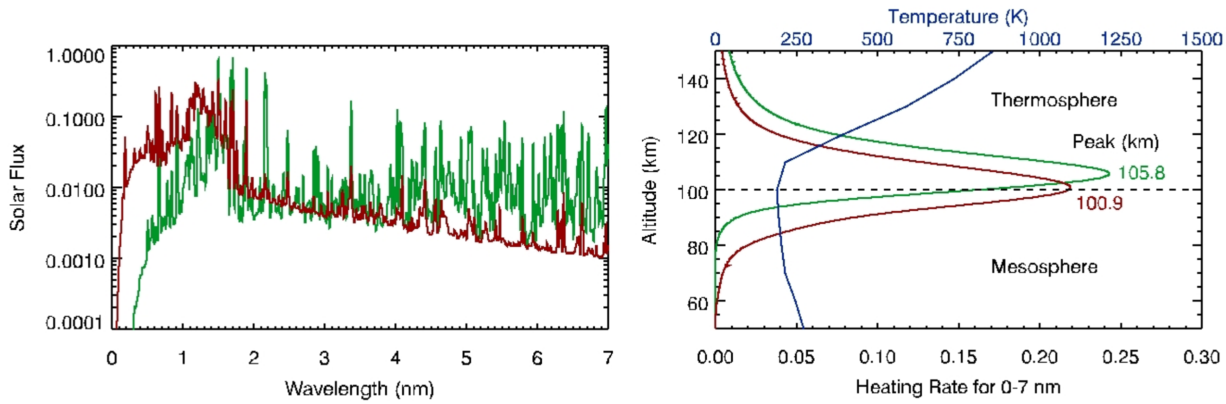


Figure 1. (*Left*) Two examples of CHIANTI model solar spectra at 0.01 nm resolution, scaled to have identical 0.1-7 nm integrated energy flux: a Sun with bright but non-flaring active regions (*green*), and a solar flare (*red*). (*Right*) Because the atmospheric cross sections decrease with wavelength in the 0-7 nm range, the different spectral distributions deposit the *same amount of energy* very differently in Earth's mesosphere and lower thermosphere: the flare spectrum is deposited at much lower altitudes. The peak height difference is ~5 km, which is comparable to the ~5.8 km scale height at the mesopause (dashed line). ***ISSUE: While we have 14 years of solar 0.1-7 nm broadband measurements, we only have models to estimate the spectral distribution in this band. Without better knowledge of the SXR spectra, there is significant uncertainty in our knowledge of how much solar SXR energy is deposited in Earth's atmosphere and also precisely where this energy is deposited in the ITM.***

There is a rich history of solar SXR measurements over the past three decades (see Figure 2), but with a significant gap of SXR measurements in the 0.5-6 nm range. There were many new discoveries about solar flares during the 1980s with solar SXR spectral measurements from the DoD P78-1, NASA Solar Maximum Mission (SMM), and JAXA Hinotori satellites. For example, Doschek (1990) provides results about flare temperatures, electron density, and elemental abundances for some flares during these missions. Sterling *et al.* (1997) also provides a review of flare measurements from Yohkoh and Compton Gamma Ray Observatory (CGRO) for the hard X-ray (HXR) range. These earlier missions laid a solid foundation about flare physics and flare spectral variability that the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the Solar Dynamics Observatory (SDO) continue on to the present time for the HXR and EUV ranges, respectively. ***With solar flare spectral variability expected to peak near 2 nm***

(Rodgers et al., 2006), in a range not measured by any spectrometer, MinXSS measurements of the solar SXR irradiance will provide a more complete understanding of flare variability in conjunction with RHESSI and SDO EUV Variability Experiment (EVE) measurements.

There are also two decades of broadband SXR measurements; these are not shown in Figure 2 as they do not provide spectral measurements. These broadband measurements cannot 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 solar SXR measurements include the two GOES X-Ray Sensor (XRS) 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; Acton *et al.*, 1999), Student Nitric Oxide Experiment (SNOE, 1998-2002; Bailey *et al.*, 2000), Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED, 2002-present; Woods *et al.*, 2005a), the Solar Radiation and Climate Experiment (SORCE, 2003-present; Woods *et al.*, 2005b), and the Solar Dynamics Observatory (SDO, 2010-present; Woods *et al.*, 2012).

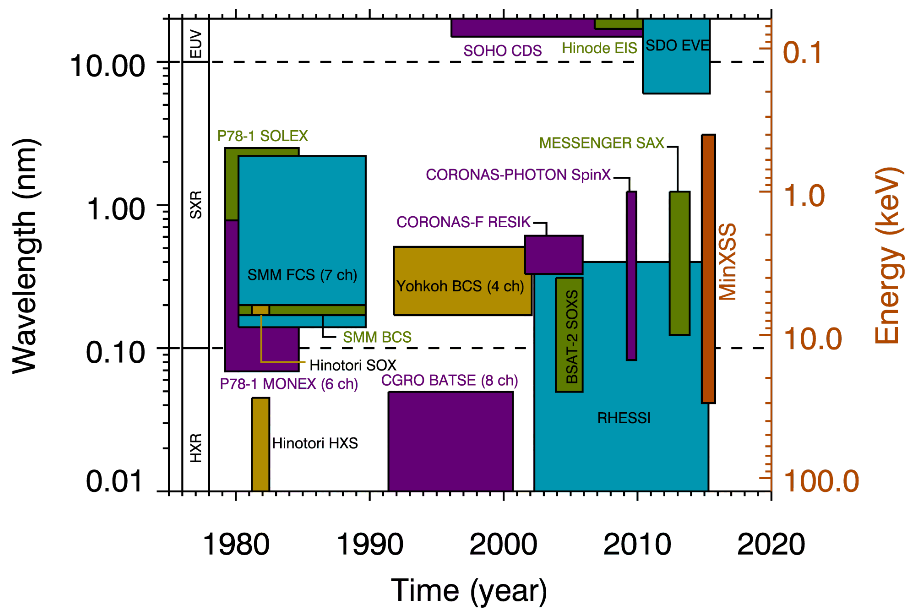


Figure 2. History of solar SXR spectral measurements. Some of these, such as SMM FCS, are scanning spectrometers that cannot make simultaneous measurements over their full spectral range, and some have low spectral resolution, such as P78-1 MONEX. ***MinXSS measures all wavelengths in its spectral range simultaneously and with high spectral resolution of 0.15 keV. MinXSS will help to fill the spectral gap between the current SDO/EVE and RHESSI spectral measurements to provide a more complete understanding of solar SXR variability.***

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 (Solomon *et al.*, 2001). 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 3; 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. (2009) 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.***

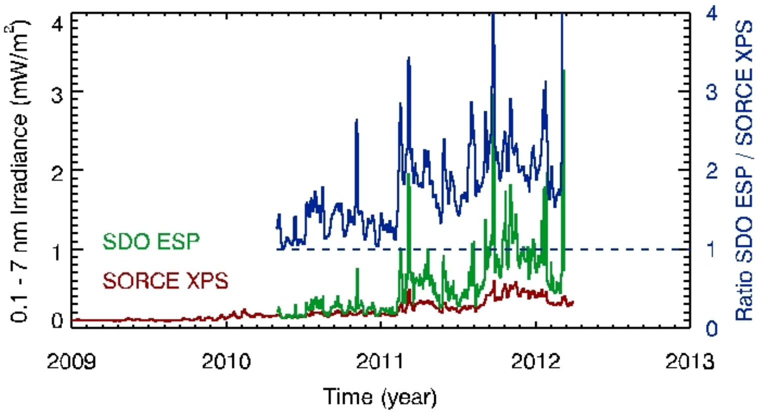


Figure 3. The solar 0.1-7 nm irradiance is currently measured by broadband SXR photometers onboard NASA's SORCE and SDO satellites. They are in very good agreement during times of low solar activity, but differ by more than a factor of 2 during times of high activity. ***ISSUE: Different spectral bandpasses could account for some of this difference, but the application of different model solar SXR spectra in the data processing algorithm is likely the primary contributor to the disagreement.***

The MinXSS solar SXR spectra are also important to address outstanding issues concerning E-region conductance that has an enormous effect on global electrodynamics 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 to ~3 nm) or at H Lyman-beta 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. If so, then the models could more accurately describe important phenomena such as magnitude and morphology of the equatorial ionization anomalies, pre-reversal enhancement of vertical electric field, and effect of tidal perturbations on the F-region.

Spectral models of the solar irradiance (e.g., CHIANTI; Dere *et al*., 1997; Landi *et al*., 2006) are needed in order to convert the broadband measurements into irradiance units. Rodgers *et al*. (2006) performed 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). Their spectrum is similar to the flare spectrum shown in Figure 1 (red line). The CHIANTI spectral model is part of their analysis and is also routinely used for processing these broadband measurements (e.g., Woods *et al*., 2008). 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 (Woods & Chamberlin, 2009; Caspi & Lin, 2010). ***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.*** To further heighten the concerns with spectral models, 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 3). These discrepancies can be partially explained by wavelength-dependent instrument calibrations, but the greater contribution is the lack of knowledge of how this dynamical part of the solar spectrum changes as a function of wavelength and time. The MinXSS instrument, Amptek X123, flew on the SDO/EVE calibration rocket payload in June 2012, and that measurement had a difference of almost a factor of 10 below 2 nm with the CHIANTI model prediction based on SORCE XPS broadband measurements. 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 the proposed MinXSS observations is to reduce these SXR spectral dif-***

ferences 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, as compared to 0.6 keV resolution by MESSENGER SAX (Schlemm *et al*., 2007). The MinXSS measurements will enable improvements to solar spectral models, such as the CHIANTI model and the Flare Irradiance Spectral Model (FISM; Chamberlin *et al.,* 2007, 2008). 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.

In summary, the solar SXR irradiance is deposited through a range of altitudes in the mesosphere and lower thermosphere. The precise altitude is dependent on the X-ray energy but is not constrained by our current set of broadband measurements. ***The new MinXSS measurements of the solar SXR spectrum will resolve how much energy is in the SXR and where in Earth's atmosphere the solar SXR energy is deposited, resolve differences between different broadband measurements, and improve upon solar spectral irradiance models.***

1.2. Education Objective and Student Involvement

A secondary objective of MinXSS is to train students as the next generation Science, Technology, Engineering, and Mathematics (STEM) workforce for space missions. There is a long history of cooperation between students at the University of Colorado, Boulder and professional engineers and scientists at LASP, which has led to many successful space missions with direct student involvement. The recent student-led missions include the Student Nitric Oxide Explorer (SNOE, 1998 – 2002), the Student Dust Counter (SDC) on New Horizons (2006 – present), and the Colorado Student Space Weather Experiment (CSSWE), being a very successful NSF CubeSat that launched in September 2012. Students are involved in all aspects of the design, and they experience the full scope of the mission process from concept, to fabrication and test, and mission operations. The MinXSS mission will continue this rich heritage.

A significant part of the student involvement is gained by using the MinXSS project as a focal point for an existing two-semester course sequence in CU's Aerospace Engineering Sciences (AES) Department: the Space Hardware Design section of Graduate Projects I & II (ASEN 5018 & ASEN 6028). The goal of these courses is to teach graduate students how to design and build systems using a requirement-based approach and fundamental systems engineering practices. The two-semester sequence takes teams of about 15 students from requirements definition and preliminary design through manufacturing, integration, and testing. In addition to the design process, students learn key professional skills such as working effectively in groups, finding solutions to open-ended problems, and actually building a system to their own set of specifications. The partnership between AES and LASP allows us to include engineering professionals in the mix, thus more effectively training science and engineering students for future roles in the civilian or commercial space industry. Included in the MinXSS program are a couple of paid student research assistants to fill critical student roles and to provide continuity across semesters.

Profs. Xinlin Li and Scott Palo have taught the Space Hardware design courses for the past 12 semesters and intend to continue these courses for a few more years. With funding for a CubeSat mission, these courses are significantly enhanced to actually build and test subsystems and to support LASP engineer mentors for a few hours per week during the semester. The mentoring process mitigates risk of the inexperience of the students and ensures system engineer oversight.

1.3. Measurement Requirements

To address the MinXSS science objective, we require measurements of the solar SXR irradiance (full-disk, not imaging) with spectral resolution better than 1 nm and with accuracy better than 30%. While simple in concept, the technology to do this in the 1-5 nm range has traditionally been difficult. Grazing-incidence grating spectrometers are only effective longwards of 5-10 nm (e.g., SDO/EVE measures down to 6 nm with 0.1 nm resolution; Woods *et al*., 2012). Bragg crystal spectrometers, often used in the 1970s and 1980s for solar SXR measurements, have extremely high spectral resolution but a very narrow range of about 1 nm (e.g., Blake *et al*., 1965), and they are large and heavy instruments. Solid-state (semiconductor) photon-counting detectors work very well for obtaining hard X-ray (HXR) and gamma ray spectra shorter than 0.5 nm (e.g., RHESSI measures up to 0.4 nm; Lin *et al*., 2002).

Silicon Drift Detectors (SDD) are the novel technology that enable new solar spectral measurements over a wider range in the SXR. The Amptek X123 SDD is a commercial off-the-shelf (COTS) instrument that we have acquired and have flown successfully on a NASA sounding rocket in June 2012 as part of our calibration program for the SDO/EVE instrument. The X123-SDD is described more in Section 2.2, but in brief, it has its own internal detector cooler and miniature vacuum system to operate at -50°C to achieve very low noise, which in turns enables an energy resolution of better than 0.15 keV FWHM. The June 2012 solar SXR measurement has provided a new solar SXR spectrum, but this single spectrum does not permit the study of time-dependent solar SXR spectral variations.

The proposed MinXSS mission, with its observations of the solar SXR over many days and different levels of solar activity, is much better suited to addressing these objectives. The expectations from any one solar rotation (27-day) period near solar cycle maximum are many C-class flares, a few M-class flares, and perhaps one X-class flare (Garcia, 2000). There are also flares during solar cycle minimum, but they are typically smaller and less frequent. Although the minimum mission requirement is just one month of solar observing, we are planning for a 3-month nominal mission and a 6-month optimal mission.

Table 1. Science Traceability Matrix.

Note 1: SDO measures > 6 nm and RHESSI measures < 0.04 nm. Flares are expected to peak near 2 nm, so it is acceptable to have a gap at 3-6 nm for a low-cost CubeSat mission.

Objective	Science Requirement	Functional Requirement	Predicted Performance	Mission Requirement
1. Understand solar SXR spectrum and its impact on ITM	Measure the solar SXR spectrum	Range: 0.1-10 nm Resolution: < 1nm Accuracy: < 30%	0.04-3 nm (*Note 1*) 0.15 keV (< 1 nm) 10%	LEO Mission (Alt. < 700 km, incl. > 35°) Solar Pointing (Acc. < 2°, Know. <0.05°) Mission > 1 month Data > 360 KB/day
	Model the ITM response	ITM GCM for altitude 80-150 km	NCAR TIME-GCM	
2. Train STEM space workforce	Teach and mentor graduate students	Graduate project course	CU ASEN 5018 & 6028 (CubeSat Project Course)	

1.4. Mission Importance

The MinXSS measurements are important for improving the understanding of the highly-variable solar X-rays and where they are deposited in the ITM. For closure on such understanding, the MinXSS data for over at least one solar rotation, including flare data, will be used as input to the NCAR/HAO Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) (Roble & Ridley, 1994) to study the solar energy deposition and how the SXR variations can affect the ionosphere through photoionization, photochemistry, and dynamical changes in the lower thermosphere and upper mesosphere. Solomon & Qian (2005) provide details on how the solar irradiance input is incorporated into the TIME-GCM and the importance of having improved solar input for ITM modeling efforts. We intend to help organize at least one CEDAR campaign during the MinXSS mission to further enhance what can be learned through combining modeling and observations of the ITM by NASA satellites (e.g., TIMED), ground-based SuperDARN network, and NSF observatories at Arecibo, Jicamarca, Millstone Hill, and Sondrestrom. In addition, the MinXSS mission is well-timed to observe near the solar cycle maximum when there are more frequent and larger solar storms. The MinXSS data products will be publicly accessible so that the larger geospace community can use them for additional studies concerning the physical processes of solar flare energy release and their impacts on Earth's atmosphere.

MinXSS has broader impacts for the USA science and engineering community by (1) advancing the understanding of solar-terrestrial interactions, (2) training the next generation STEM workforce in instrumentation, satellite technology, and science data analysis, and (3) developing transformative CubeSat technology including a miniaturized solar X-ray spectrometer, high-precision ADCS, and deployable high-power solar arrays.

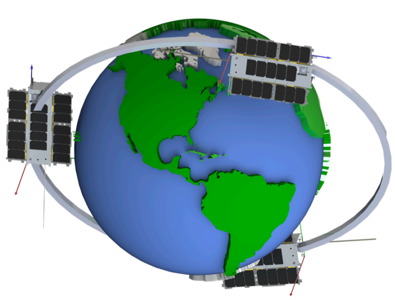
1.5. Relevance to NASA Science Plans

The proposed work of studying the ITM response to the measured solar SXR radiation directly pertains to NASA's 2012 Decadal Survey in Solar and Space Physics Goal 2 to "determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs". The MinXSS science analysis will contribute to answering a key ITM question: what is responsible for the dramatic variability in many of the state variables describing the ionosphere thermosphere mesosphere (ITM) region? Considering that there is, on average, at least one major flare / solar storm per month (Garcia, 2000), the MinXSS mission of 1-6 months is expected to provide substantial measurement input for models to constrain some of the dramatic variability effects in the ITM during such solar storms.

The study of flares with the MinXSS data will contribute to the 2012 Heliophysics Decadal Survey Challenge SH-3 to "determine how magnetic energy is stored and explosively released". Detailed studies of the measured SXR flare spectra will reveal new results on the hot corona and relationships between thermal and non-thermal emissions, which in turn can help improve the understanding of the impulsive energy release and particle acceleration processes in flares. With respect to NASA's 2010 Science Plan, this work addresses the Science Question "What causes the Sun to vary?" and the Science Area Objective 1 for Heliophysics.

Furthermore, the MinXSS CubeSat mission can be a contribution to the Heliophysics 2012 Decadal Survey DRIVE initiative to "diversify observing platforms with microsatellites".

Table 2. MinXSS Mission Orbital Requirements and Reference (Example) Orbit.
The attitude is controlled such that the solar panels and instrument apertures are Sun-pointed, the antenna is parallel to the ground, and the other three long sides with radiators face mostly towards deep space.



Orbital Parameter	Requirement	Reference Orbit
Altitude	< 700 km (CubeSat)	450 km x 600 km
Inclination	> 35° for LASP GS (37º - 55º optimal)	50°
Eccentricity	Any	0.01
Period	N/A (calculated)	95.1 minutes
Eclipse	N/A (calculated)	34.9 minutes
Spacecraft Size	3U (CubeSat)	3U (CubeSat)
Mass	< 4 kg (CubeSat)	3.5 kg
Orbit Average Power	> 10 W	12.5 W
Data Per Day	> 360 KB/day	~ 432 KB/day
Ground System	UHF Radio	GS at CU/LASP
Downlink Time	> 10 min/day	> 12 min/day

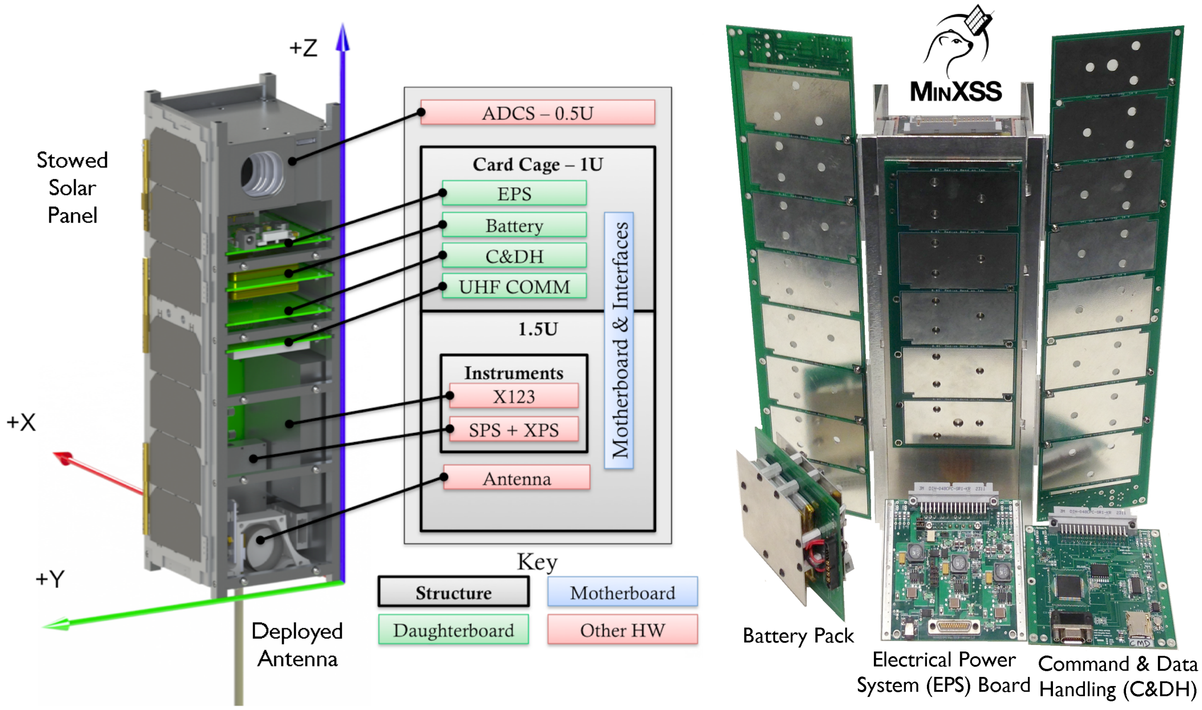


Figure 4. SolidWorks rendering of –X axis view and System Block Diagram are on the left. The flight units of the battery pack, EPS, C&DH, and structure, along with the prototype solar panels (deployed, and without cells installed), are shown on the right. Acronyms: Command and Data Handling (C&DH), Electrical Power System (EPS), Communications (COMM), Attitude Determination and Control System (ADCS), Solar Position Sensor (SPS), X-ray Position Sensor (XPS), X123 is Amptek X123 spectrometer.

2. Methodology / Mission Implementation

As the solar SXR radiation does not reach the ground, space flight is required for the proposed measurements. The proposed X123 instrument has flown successfully on a NASA sounding rocket flight (June 23, 2012) and has provided a spectral measurement of the SXR irradiance during quiet solar conditions. As the short-duration rocket flights are not likely to measure a solar eruptive event and are not feasible for multiple flights for solar rotation studies, the next step is to fly the X123 on a satellite. Only a short duration mission is needed to initially characterize a solar rotation and a few flare events in the SXR range, so we have developed the MinXSS CubeSat mission for addressing this need. This section provides overviews of MinXSS subsystems.

The 3-Unit (3U) MinXSS structure is partitioned into three basic blocks (Figure 4): 1.5U for the solar instruments (COTS Amptek X123 spectrometer and SPS/XPS), 1.0U for system electronics, and 0.5U for the attitude determination and control system (ADCS). (1U is defined as the standard CubeSat dimensions of 10.0 cm x 10.0 cm x 11.35 cm.) There are three solar panels to provide 22W when in sunlight; a body-mounted solar panel (2U surface area: 10 cm x 22 cm) fixed to the solar-oriented side, and two deployed panels (each has 3U surface area). The deployable UHF antenna, UHF Communication, and Electrical Power System (EPS) are heritage from CSSWE (NSF CubeSat at CU, launched in Sep. 2012 and still operating). The ADCS will maintain the spacecraft orientation such that the solar panels and instruments are Sun-pointed, the antenna is along orbit track for optimal ground communication performance, and at least one of the radiator sides is oriented towards zenith (deep space) (Table 2).

The resources for the MinXSS subsystems are listed in Table 3. The MinXSS design is mature as it has been iterated for 2 years as a CU graduate student project and has already had a Preliminary Design Review (PDR) and Critical Design Review (CDR). All of the subsystems have had an engineering unit built, and there are flight units for the X123, C&DH, EPS, and COMM. A margin of 20% is reasonable for this stage of development; so MinXSS has adequate margin.

The functional block diagram in Figure 5 shows more details of the electrical functions. Each subsystem is discussed in more detail in subsections, but we first discuss the spacecraft structure.

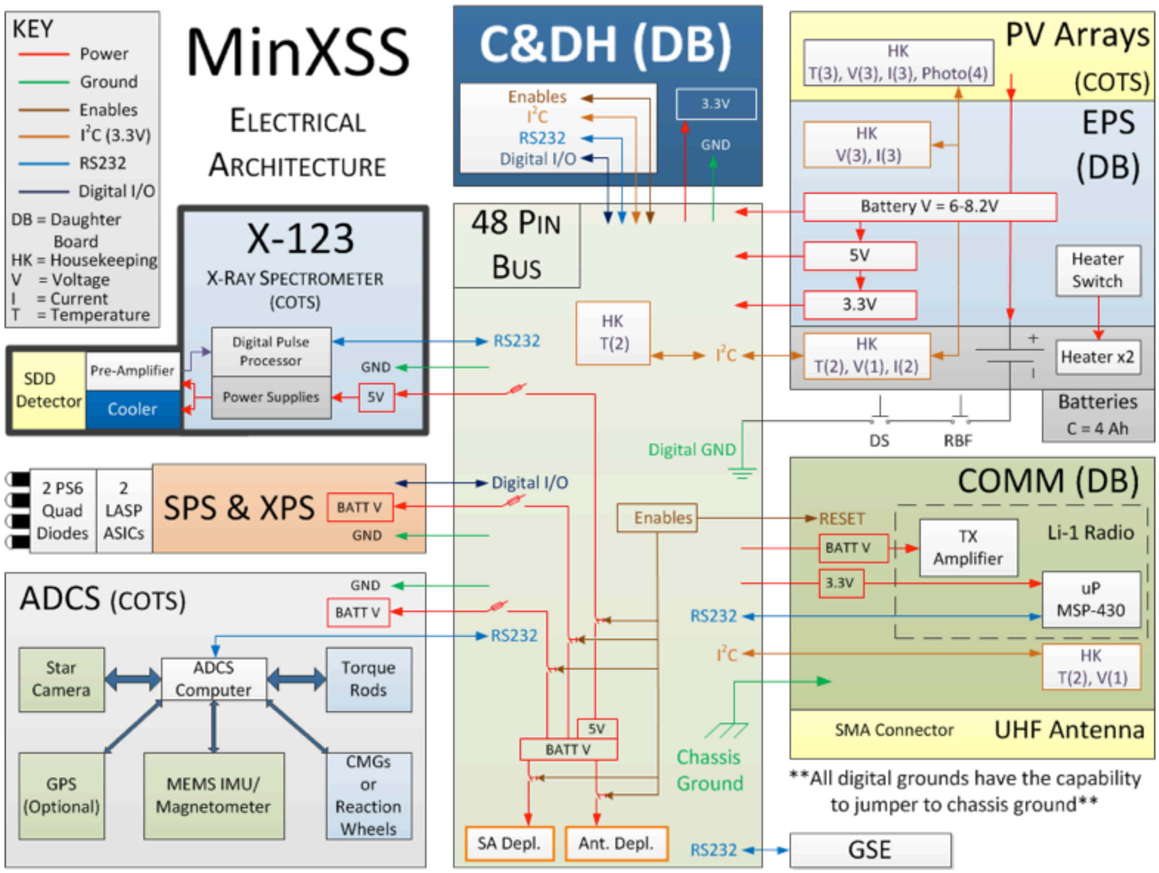


Figure 5. Functional block diagram of the MinXSS subsystems.

Table 3. MinXSS resources by subsystem. A 1U volume is 10 cm x 10 cm x 11.35 cm = 1135 cm^3.

Subsystem	Estimate / Actual	Volume (cm^3)	Mass (g)	Average Power (W) / Peak Power (W)
Amptek X123-SDD X-ray Spectrometer	Amptek Actual	175	180	2.5 / 5.0
Lithium-1 Radio UHF COMM	CSSWE Actual	144	164	1.1 / 4
BCT XACT ADCS	BCT Estimate	500	700	0.5 / 2.0
(CU) Solar Panels	CU Estimate	110	320	N/A
(CU) C&DH	MinXSS Actual	120	43	0.2 / 0.7
(CU) EPS + Battery	MinXSS Actual	390	294.4	1.7 / 3.0
(CU) SPS and XPS	CU Estimate	206	162	0.8 / 0.9
(CU) Thermal Radiator / Heaters	CU Estimate	184	94	0.7 / 3.0
(CU) C3 Structure / Motherboard	CU Actual	435	800	N/A
Total		2264	2759	7.5 / 18.6
Limit for Volume/Mass, Goal for Power		3405	4000	10 / 20
% Margin =((Allowed – Total)*100)/Total		34%	31%	25% / 7%

With goals of having conductive paths from the internal electronics out to radiator surfaces and to have individual electronics boards accessible, the CU AES Space Hardware Design (CubeSat) Fall 2011 class[1] developed a new CubeSat bus structure named the CubeSat Card Cage (C3). The C3 module includes a 1U structure with a backplane to eliminate most cabling and has structural support (slots) for electronics boards. It uses the all-metal Unitrack Kooler Guides to secure the cards and conduct some of the boards' heat out to the C3 outer plates that serve as radiators. There can be as many as 5 boards per 1U. The MinXSS students fabricated a prototype 3U structure in 2011 and built an improved structure in 2013. SolidWorks stress analysis by students has validated the flight structure capability. Vacuum testing has validated the thermal capability.

The LASP rocket program also adopted the C3 last year and built up a set of electronics to control a prototype GOES-R X-Ray Sensor (XRS) and an X123 spectrometer. Figure 6 shows this rocket 1U C3 system that flew successfully on June 23, 2012 as part of the SDO/EVE underflight calibration experiment. This rocket program provides verification of the C3 design, prototype C&DH and flight software, and X123 spectrometer performance for solar observations.

Much of the MinXSS spacecraft is designed and built by the CU AES CubeSat class students, but there are 4 major purchases for the mission. The ADCS is from Blue Canyon Technology (BCT), with Maryland Aerospace Incorporated MAI-400 unit as backup. The triple junction (TJ) solar cells are from Emcore, with AzurSpace cells as backup. The MinXSS science instrument, Amptek X123-SDD, and the Lithium-1 Radio UHF COMM module have already been acquired.

2.1. Mission Orbit

Due to the altitude restrictions placed on CubeSats, MinXSS will operate in a low Earth orbit (LEO). While any orbit inclination is acceptable to meet science requirements, an inclination greater than ~35° is needed to utilize LASP's existing UHF ground station (40° latitude). If a viable launch opportunity was available for a lower-inclination orbit, we could consider a different location for our CubeSat ground station.

Tables 1 and 2 list the mission requirements for MinXSS. We chose a reference orbit of 50° inclination to reflect a reasonable orbit that would allow the satellite to be launched from any of the USA mainland launch sites (Kennedy, Vandenberg, Wallops). The reference orbit is just an example to refine the power and thermal environment for the proposal; many other orbit options are viable for MinXSS due to its flexible mission requirements.

The MinXSS satellite will have at least two opportunities every day to contact the existing UHF CubeSat ground station at LASP in Boulder, CO with a minimum daily access time of about 15 minutes for the reference orbit. With downlink at 9600 baud using LASP's amateur radio, a factor of 2 for communication and packet overhead, and assuming at least 12 min per day actual downlink time, the minimum science data that can be downlinked per day is 432 KB (1 KB = 1000 bytes). The CSSWE contact time is actually more than 20 min per day. The science data rate will be tailored to meet this minimum data rate (see Section 2.2) and can be changed via commanding in-flight. Section 3.6 describes the early orbit operations.

2.2. X123-SDD Spectrometer

The MinXSS mission science objective for understanding ITM energetics requires an instrument to measure the solar SXR irradiance with spectral resolution better than 1 nm and with accuracy better than 30%. The optimal wavelength range to observe is between 0.5 and 2.5 nm, as the radiated solar SXR energy peaks in this range. In energy units ($E = hc/\lambda$), this range corresponds to 0.5 to 2.5 keV (a 1-nm photon has 1.24 keV of energy). The commercial off-the-shelf (COTS) solution for such an X-ray spectrometer is the Amptek X123 Silicon Drift Detector

[1] C3 design web site is http://www.thesciencecollective.com/ctide/cubesat-card-cage

(SDD). This X-ray spectrometer measures individual photons with energies from 0.4 keV to above 30 keV (0.04 nm to 3 nm). The spectral resolution of ~0.15 keV FWHM is almost constant in energy units; expressed in wavelength, it varies from as little as 0.0002 nm FWHM at 0.04 nm up to 1 nm FWHM at 3 nm. The accuracy requirement is met by calibrating the X123 to better than 10% using the NIST Synchrotron Ultraviolet Radiation Facility (SURF). This X123 SURF calibration was completed in November 2012. The SXR range is not very sensitive to contamination (unlike EUV optics); we are expecting less than 5% of in-flight degradation (e.g., SDO/EVE 0-7 nm channel has seen less than 1% degradation over 3 years).

The X123-SDD is an advanced X-ray spectrometer with an active area of 25 mm^2, an effective Si thickness of 0.5 mm, an 8-µm-thick Be filter on the detector vacuum housing, an active 2-stage thermoelectric cooler (TEC) on the detector, and sophisticated multichannel analyzer (MCA) detector electronics. The thickness of the Si determines the high energy (short wavelength) sensitivity limit, and the thickness of the Be filter sets the low energy (long wavelength) limit. The X123 is ~0.1U, requires 5V input power (2.5 W operating, 5 W peak) and has RS232 serial interface. The X123 measures the energy of individual X-ray photons and accumulates a spectrum with user-configurable integration time, gain, and dynamic range. For MinXSS, it will output 1024 spectral bins up to 30 keV, thus having 5 bins per 0.15 keV resolution. The X123 cooler is commandable to any temperature within 70°C of the base temperature.

Figure 6. The X123-SDD X-ray Spectrometer is shown with the CubeSat Card Cage. These flew successfully on NASA rocket on June 23, 2012.

A 350-µm-diameter aperture is used to prevent count-rate saturation during large flares (e.g., GOES class X10) without significantly compromising low-activity observations (Figure 7). The X123 maximum count rate is ~200,000 events/sec. An external baffle limits the field of view to ±4°.

The X123 cadence is set by the downlink budget. At 1024 spectral bins and 24 bits/bin, each X123 spectrum is ~3 KB (~1.5 KB compressed), so there can be at least 275 spectra/day. So that flares can have higher time cadence for studying energetic processes, the X123 integration time will be 1 minute and continuously buffered. Every 5 minutes, the C&DH will analyze the spectra in the buffer to determine (based on a heuristic algorithm) whether a flare occurred. If so, the 1-minute-cadence data will be directly stored; if not, the spectra will be decimated into a 5-minute average for storage. Table 4 shows the data volume range that could be generated each day in flight. The daily downlink example can usually accommodate the 1-2 major (M- or X-class) flares per day (Garcia, 2000). As the C&DH SD card can hold more than a year of data, any day with numerous flares can have some of its

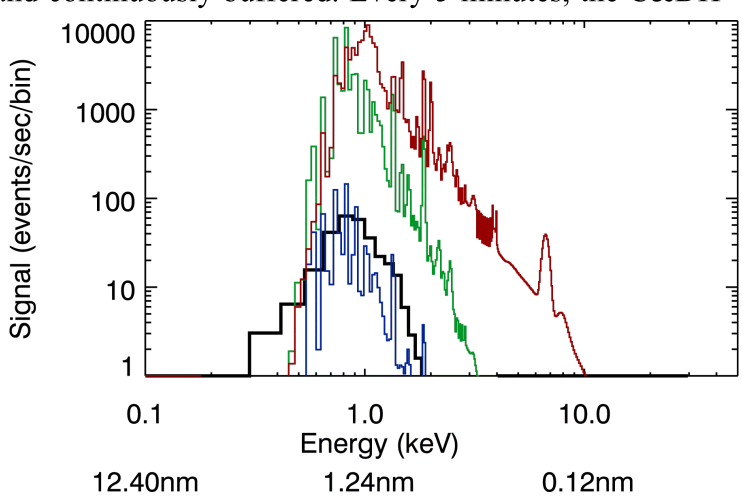


Figure 7. Signal estimate for the X123-SDD X-ray Spectrometer for worst-case conditions: solar cycle minimum (blue), solar cycle maximum (green), and large flare (red). The CHIANTI model in 0.03 keV bins is used for the signal estimates and then smoothed by 5 bins for X123 resolution. The aperture is 350 µm diameter, yielding a total count rate of 800, 43,000, and 120,000 counts/sec (cps) for the blue, green, and red spectra, respectively. The black spectrum is the 23 June 2012 rocket measurement for the X123 during quiet solar conditions, but taken in 256 bins instead of the MinXSS planned resolution of 1024 bins. This rocket spectrum of 1073 cps agrees very well with the low signal prediction, but it does not show the 0.15 keV resolution capability due to the 256-bin readout for the rocket X123.

data downlinked later on days with fewer flares. The flare-detection threshold, nominal integration time, and decimation factor can be commanded on-orbit to optimize the average data volume for the specific flare activity level.

Table 4. Generated data volume per day, including 63% duty cycle and factor-of-2 compression.

Case	Flaring Time [min]	Non-Flaring Time [min]	Flare Data [KB] (1-min cadence)	Non-Flare Data [KB] (5-min cadence)	Total Data [KB]
Min. (no flares)	0	910	0	285	280
Daily Downlink	110	800	172	251	423
Max. (all flares)	910	0	1427	0	1398

2.3. SPS / XPS Quadrant Diodes

The Solar Position Sensor (SPS) and X-ray Position Sensor (XPS) are Si quadrant diodes (Opto Diode Corp. AXUV-PS6) with a visible neutral density filter and X-ray Be foil filter, respectively. The SPS has a field of view of ±6° and provides solar pointing knowledge to better than 1 arc-min (3-sigma), and its pointing information can be used by the ADCS for closed-loop control. The XPS provides flare location, to better than 1 arc-min for X-class flares and better than 10 arc-min for M-class flares. These sensors have been developed at LASP for the NOAA GOES-R EUV X-ray Irradiance Sensors (EXIS), and the GOES-R program has agreed to donate diodes and ASIC electrometers for the MinXSS mission. LASP has flown versions of SPS on TIMED, SNOE, and SORCE. The MinXSS student team built a prototype SPS/XPS and housing already, and they will be building the flight version this fall. Neither the SPS or XPS are required for the MinXSS science requirements, so they are descope options in case there is any conflict in meeting the CubeSat resource and budget requirements.

2.4. C&DH and Flight Software

Microcontroller. The core of the MinXSS Command and Data Handling (C&DH) subsystem is a low-power Microchip dsPIC33 Microcontroller Unit (MCU, MC dsPIC33EP512MU810). C&DH communicates with and control the X123 instrument via RS232, EPS, ADCS, and UHF COMM via I2C, and SPS/XPS via direct DIO. Additionally, C&DH handles all housekeeping monitoring and data manipulation. Data are stored on a 2 GB Secure Digital (SD) memory card until transmission. This SD card can store more than 1400 days (3.8 years) of data. A real-time clock (RTC) IC provides precise time knowledge. The dsPIC33 and external RTC watchdog timers can be used to initiate a reset of the system in case it becomes unresponsive. The MinXSS 1-year mission worst-case radiation dose estimate is 4 kRad, assuming a minimum shielding of 1 mm of Al. The C&DH board successfully passed radiation tests of 10 kRad and 25 kRad. The interfaces between the C&DH and all other devices have already been developed and tested. Two copies of the flight C&DH were built and tested this spring/summer.

Flight Software. The student team has been developing the MinXSS flight software for over a year now. The software manages the EPS, controls and reads the X123 X-ray spectrometer (including buffering and decimation of generated spectra), reads the SPS/XPS data, communicates with the ADCS, and manages the UHF COMM board for receiving and executing uplinked commands and for downlinking data. Most of the flight software modules have been completed with the exception of the decimation and compression of the X123 data and communication with the ADCS; both modules will be the focus for the Fall 2013 class. The flight software allows in-flight commanding of various settable parameters, including the X123 integration time, decimation factor, thresholds for the heuristic flare-detection algorithm, and time ranges for selective data downlink. The LASP flight software group, who served as mentors for CU's CubeSat CSSWE and also for MinXSS, has extensive experience programming NASA flight processors.

The software is built on a Slot Real-Time Operating System (RTOS), based in C code developed at LASP (heritage: CCSWE, SDO/EVE rocket experiment, GOES-R, MAVEN). The key elements of the software design are robustness and simplicity, with the health and safety of the satellite as top priority. Because many of the tasks performed by the C&DH are not time-sensitive and can be handled at any time in the slot process, the real-time demands on the C&DH and flight software are very low. The flight software is written in C for the dsPIC33 architecture, a task well-suited to the student team with experienced mentors. Much of the flight code has already been tested on the successful rocket flight with X123 and XPS instruments in June 2012.

2.5. ADCS

In order to provide a stable view towards the Sun for the X123 solar observations and to maintain appropriate antenna orientation during ground contacts, MinXSS has an Attitude Determination and Control System (ADCS). With the wide field of view of the X123 (±4°), the pointing requirements for MinXSS are only 2° (3-sigma) accuracy and 0.05° (3-sigma) knowledge.

The commercial CubeSat ADCS selected for MinXSS is the fleXible ADCS Cubesat Technology (XACT) from Blue Canyon Technologies (BCT). BCT has developed a 0.5U-sized ADCS unit (0.7 kg) utilizing miniature reaction wheels, torque rods, and star cameras for the Air Force under a Small Business Innovation Research (SBIR) Phase II program, and the first flight-ready XACT ADCS module will be completed this fall. The BCT XACT is expected to provide pointing accuracy and knowledge of better than 0.02° in all 3 axes. The XACT interface utilizes 5V power input (0.5 W nominal, 2.0 W peak) and serial communication (RS422, SPI, or I2C). Additional information about XACT is given in the BCT quote in the budget section.

If the XACT does not meet its development goals, the Maryland Aerospace Inc. (MAI) MAI-400 0.5U ADCS module is a backup option for MinXSS. The MAI-400 is comparable to the BCT XACT in cost, mass, and power, but has poorer pointing accuracy (~0.2° in all 3 axes) using Earth horizon sensors. However, it still meets the requirements for the MinXSS mission.

The SPS instrument provides 2-axis (pitch/yaw) pointing knowledge on the Sun. Both BCT XACT and MAI-400 ADCS modules can use the SPS solar position data for attitude control.

2.6. EPS Power and Solar Panels

MinXSS will use the CSSWE-heritage Electrical Power System (EPS) design. CSSWE's EPS uses high-efficiency buck converters for power regulation to 3.3 V and 5 V and a simple battery charging logic for use with Li-polymer batteries. This EPS / battery design is ideally suited for the MinXSS spacecraft design that requires the same voltages with a nominal power of 7.5 W and peak power of 19 W. The MinXSS EPS board is a new design though for higher power, more monitoring capability, and to interface to C3 backplane. Two EPS flight boards were fabricated and tested this summer. The battery pack uses four SparkFun 2-Ah Li-Ion batteries configured as two parallel sets of two batteries in series to provide a 6-8.2 V unregulated 4-Ah bus.

Using the CSSWE heritage solar panels built at CU, the three solar panels on MinXSS uses Emcore triple junction (TJ) coverglass interconnected cells (CIC). As backup, we could purchase TJ cells from AzurSpace or even CubeSat solar panels from Clyde Space or Pumpkin. One solar panel is fixed on the solar-oriented side (2U area with 5 cells), and the other two are deployed solar panels (each with 3U area and 8 cells). As MinXSS is a Sun-pointed spacecraft, these solar panels can nominally supply 22 W (EOL value) during the orbit day (~60 min). There is adequate margin for operating all MinXSS subsystems and for charging the battery with this configuration so that instruments will not have to be cycled on/off during each orbit eclipse.

MinXSS is still a viable science mission even if one or both of the solar panels fail to deploy. The fixed panel provides 5.5 W of power, which is enough to operate the MinXSS minimal power load of 3.1 W (X123, SPS, XPS, and COMM off). The stowed solar panels have exposed solar cells so MinXSS could also operate for part of the dayside orbit with a 45° tilt along the spacecraft long axis to maximize illumination of two solar panels for about 10 W of power. For the failed panel deployment scenario, MinXSS would operate in its minimal load for eclipse and the first half of the orbit day, and then turn on X123 for ~30 min of solar observations. Because X123 needs less than 2 minutes to cool down and stabilize at -50°C, the majority of the solar observing period can still make quality measurements. For these operations, COMM would only be used during orbit dayside.

2.7. Thermal Design

In normal operations, MinXSS has the +X side facing the Sun and the –Y face pointing toward deep space (see Figure 4 & Table 2). Thermal Desktop analysis shows that this configuration easily satisfies all component operational and survival temperature requirements. As an example, Figure 8 shows Thermal Desktop model result for the hot case for the reference orbit (Table 2). Thermally isolating standoffs are used for mounting the body-fixed solar panels so that despite solar panel temperatures swinging between -20ºC and 75ºC, the components in the system remain within their requirements. All sides of the spacecraft not facing the Sun are used as radiators by placing various amounts of aluminum-Kapton tape on their outer surfaces. These radiator plates remain cold at all points in the orbit, ranging from -28ºC to -11ºC.

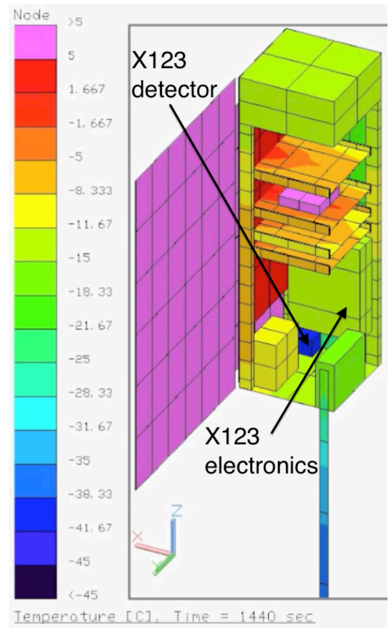


Figure 8. Thermal model hot-case prediction for MinXSS.

Temperatures are actively controlled in two places in the system: the battery using two heaters and MLI thermal blanketing, and the X123 detector head, which includes a Thermal Electric Cooler (TEC). Following the successful implementation of CSSWE's battery heaters, MinXSS's battery heater will be on when the battery temperature is between +5ºC and +10ºC. The battery heater power, as predicted by Thermal Desktop, is 0.5W – 0.8W orbit average depending on the orbit beta angle. The TEC can maintain a temperature differential of 70ºC, which has been tested and confirmed under vacuum in our lab. The requirement on measurement noise translates to maintaining the X123 detector head at -50ºC ±20ºC, thus the warm side of the TEC must be kept below +40ºC. This is easily satisfied by strapping the TEC's warm side to the –Y radiator plate, which is always below -10ºC. The MinXSS thermal design has proven to be robust, and radiator surface area can be tuned following its thermal balance test.

2.8. UHF Communication

Both the Lithium-1 Radio UHF COMM module from Astronautical Development LLC and the CU-made antenna that were used for CSSWE will also be employed for MinXSS. The antenna is a deployable spring steel (tape-measure) with a length of 34.3 cm. The MinXSS project is able to take advantage of the significant amount of effort done by the CSSWE students and mentors to optimize the CubeSat communication system, such as modeling and verifying the link margin, acquiring frequency approval from the FCC, obtaining amateur radio licenses, and developing flight software code that uses AX.25 packetization and CCSDS headers for the command and data packets. Prof. Scott Palo and consultant Jim White were the primary mentors for the CSSWE UHF COMM development and are also part of the MinXSS program.

2.9. Ground System

MinXSS will utilize the LASP ground station built for CSSWE. This ground station includes a Kenwood TS-2000 UHF radio and PC software that interfaces to a Mirage D1010-N power amp and SSB SP-7000 low-noise amplifier interface to the ground antenna. The 226-inch-long antenna (M2 436CP42 U/G) is actively controlled during the CubeSat contact using a Yaesu G-5500 Az/El rotator and GS-232A controller that interface to a PC computer. This ground system has been used for daily operations for CSSWE since September 2012 and will be time-shared with MinXSS in the event that CSSWE overlaps with the MinXSS mission.

Table 5. Data Volume Estimate over the Full Mission (in MBytes).

Mission Duration	On-Board Storage	Level 0	Level 1	Level 2	Level 3	Total L0-L3
Minimum: 1 mon	43 MB	14 MB	120 MB	120 MB	2 MB	256 MB
Nominal: 3 mon	128 MB	40 MB	320 MB	320 MB	6 MB	771 MB
Optimal: 6 mon	256 MB	80 MB	640 MB	640 MB	12 MB	1542 MB

2.10. Data Processing, Data Distribution, Science Analysis

The mission data are sorted into engineering housekeeping data and science data, then processed into data products with one file per day per product level. We refer to the raw telemetry packets as Level 0. Per Table 5, we expect to be able to downlink all of the data generated during the mission, although higher-than-anticipated flare activity or an intentional reduction of the X123 integration times and/or decimation fraction may require us to downlink less than what is stored on-board. The science processing includes higher level products: Level 1 for the data at instrument resolution and highest time cadence in solar spectral irradiance units, Level 2 for the solar irradiance data rebinned into wavelength instead of energy, and Level 3 for the daily average solar spectral irradiance. The estimated data volume in Table 5 assumes a nominal 430 KB/day downlink rate; only 1542 MB storage is required for the optimal 6-month long mission.

Because the X123 measures photon energies, it is a straightforward (direct) calculation to convert the X123 spectra (photons/bin) into solar spectral irradiance units (W/m^2 per keV or per nm). Background subtraction and corrections for aperture area, integration time, responsivity, and any non-linearity are the primary parameters in this conversion (e.g., see Woods *et al*., 2005a). There are also other small corrections, such as gain changes with temperature and responsivity changes with pointing offsets. The responsivity is established with calibrations at NIST Synchrotron Ultraviolet Radiation Facility (SURF: completed in November 2012) and validated with models of Be filter transmission and Si absorption (e.g., Henke *et al*., 1993).

Distribution of the data products is planned through the existing LASP Interactive Solar Irradiance Datacenter (LISIRD). FTP file transfers of MinXSS data products will also be available. We will make the MinXSS data products publicly available after a 1-2 month validation period. LISIRD maintains its data and meta-data in a database, and the interactive web interface provides the requested data in a variety of formats: ASCII text, netCDF, FITS, and IDL save sets. Useful mission documents, data user guide, published papers, and software tools (usually in IDL) for reading and plotting the MinXSS data will also be provided on a MinXSS project web site on CU/AES web server. The LISIRD databases are designed for large (TB) data sets, and MinXSS full mission data set is not even 2 GB. So all of the MinXSS data will be kept on-line, along with multiple copies on tape as part of the LISIRD backup system. We intend to preserve public access of the data for the life of the LISIRD system. However, LISIRD is not configured, nor funded, to be a long-duration archive center, so MinXSS archive will be at a NASA archive site.

Science analysis of the MinXSS data includes solar physics research into the causes of the solar SXR variability and the release of energy during flares, as well as improvement of the Flare Irradiance Spectral Model (FISM: Chamberlin *et al.,* 2007; 2008) by including the MinXSS measurements. Complementary data from SDO at longer EUV wavelengths are useful for more advanced diagnosis of flare temperatures, electron density, and elemental abundances, and data from RHESSI at shorter HXR wavelengths help with separating out the thermal and non-thermal radiation contributions. In addition, solar-terrestrial interaction research will include using the measured solar SXR spectra as input to the NCAR/HAO TIME-GCM. This ITM model provides the means to perform detailed studies of where the solar SXR energy is deposited and how the SXR variations can affect the photochemistry, ionosphere, and dynamics (winds/tides) changes in the lower thermosphere and upper mesosphere. The MinXSS science team will publish papers concerning the instrument design / calibration, data processing algorithms, and scientific results.

2.11. Technology Readiness / Heritage

The technology readiness of the MinXSS subsystems is extremely high for a CubeSat mission. The EPS, UHF COMM (Li-1 radio), Emcore TJ cells, and Ground System for MinXSS are the same as for the NSF CubeSat CSSWE mission. The Amptek X123-SDD X-ray spectrometer and LASP SPS/XPS are well-established sensors with flight heritage and do not require new development. The C&DH consists mostly of the Microchip dsPIC33 MCU and an SD memory card, and the Slot RTOS flight software has been extensively used for many LASP missions, including the rocket X123 experiment. The CubeSat Card Cage (C3) was developed in 2011-2012 and was flown with an X123 spectrometer on a NASA sounding rocket flight in June 2012.

The three highest-risk subsystems for MinXSS are the ADCS, deployable antenna, and deployable solar panels. MinXSS is still a viable science mission even if one or both solar panels do not deploy (see Section 2.6 for more details). The antenna and solar panels both use spring-loaded deployment systems that are released by melting a monofilament cable, and each has redundant release circuits. Even if both cable releases fail, ***nylon*** monofilament loses about 20% of its strength for every 100 hours of ultraviolet sunlight exposure and is thus expected to spontaneously release within a month of launch under the mechanism spring tension. If the antenna doesn't deploy then there will be limited, if any, communication. If the ADCS does not provide reasonably good pointing of ±2° towards the Sun, then MinXSS might have very little science return. For this reason, we will carefully review the performance results of the BCT XACT that is being delivered this fall for the AF SBIR-II. The MAI MAI-400 ADCS module is a backup ADCS unit for MinXSS. If the ADCS were to fail in flight, MinXSS could still have engineering merit in studying the spacecraft ADCS performance anomalies and issues, and the education objective can still be met in training aerospace students regardless of flight success.

Table 6. MinXSS Subsystem Heritage and Technology Readiness Level (TRL).

Subsystem / Component	COTS / Developed	TRL	Heritage
X-ray Spectrometer	COTS Amptek X123-SDD	7	SDO/EVE rocket flight (June 2012) (TRL 9 for XR100-Mars Pathfinder)
Solar Panel	COTS - Emcore TJ cells	9	NSF CubeSat CSSWE (Sep 2012)
Solar Panel Deployment (same as Antenna)	Developed at CU	7	NSF CubeSat CSSWE (Sep 2012)
ADCS	COTS - Blue Canyon Tech.	6	AF SBIR I-II (2011-2013)
UHF Radio	COTS - Lithium-1 Radio	9	NSF CubeSat CSSWE (Sep 2012)
Antenna & Deployment	Developed at CU	9	NSF CubeSat CSSWE (Sep 2012)
C&DH Flight Software	Developed at CU	7	NSF CubeSat CSSWE (Sep 2012) SDO/EVE rocket flight (June 2012)
EPS + Battery	Developed at CU	9	NSF CubeSat CSSWE (Sep 2012)
SPS and XPS	Developed at CU	8	GOES-R EXIS (2008-2013) (EXIS FM#1 delivered in Apr 2013)
CubeSat Card Cage(C3)	Developed at CU	7	SDO/EVE rocket (June 2012)
Ground Network	Developed at CU	N/A	NSF CubeSat CSSWE (Sep 2012)

3. Management and Other Mission Plans

3.1. Management Plan and Responsibilities

Management of MinXSS is the direct responsibility of the Principal Investigator (PI), Dr. Thomas Woods. He has 30 years of experience in leading successful space-based instrumentation (e.g., TIMED/SEE and SDO/EVE) and PI-led missions (SORCE) for NASA, including 20 low-budget sounding rocket experiments, and is ideally suited to lead a CubeSat project. Professors Xinlin Li and Scott Palo are the PI and Co-PI, respectively, of the successful NSF CubeSat CSSWE program and are also the long-time professors of a well-established space hardware design class. Dr. Palo also manages the dedicated CubeSat lab in the AES department. Dr. Amir Caspi and Dr. Andrew Jones are solar physicists at LASP who will provide mentoring and advice for the science instruments and flare physics research, and Dr. Caspi will lead the development of the data system, science data processing algorithms, data validation, and data distribution. Mr. Rick Kohnert is the MinXSS program manager / system engineer mentor, and he will lead a team of LASP engineer mentors, who have extensive experience designing, building, testing, and operating successful space flight missions. Dr. Stanley Solomon at HAO/NCAR will lead the atmospheric modeling and interpret the atmospheric effects due to solar SXR variations. Dr. Phillip Chamberlin at GSFC developed the Flare Irradiance Spectral Model (FISM), and he will use the MinXSS measurements to update FISM in the SXR range and to provide additional solar irradiance predictions from FISM as input for ITM studies using HAO/NCAR atmospheric models. Mr. Scott Schaire at GSFC/WFF is supporting some of the MinXSS integration and test and is our liaison to the NASA/KSC NASA/KSC Launch Services Program (LSP). More details on each person's experience are provided in their biographical sketches.

Students are an integral part of the project, providing leadership, design work, analysis, manufacturing, integration, testing, and mission operations. Students become involved with the project through the two-semester graduate projects class. Those students who excel and show an interest in continuing to contribute to the project have the option to receive independent study credit for an additional two semesters, as well as paid internships during the summer. The structure of the student team is modeled on the NSF CubeSat CSSWE and the space hardware design class, with a Project Manager (PM) and Systems Engineer (SE) leading and coordinating the efforts of Lead Engineers for each spacecraft subsystem and ground data system. Emphasis is placed on obtaining a PM and SE that can lead the project for long durations, in order to increase the level of continuity between semesters. The current PM and SE are Samantha Liner and James Mason, respectively, and both plan to continue independent study for MinXSS. Personnel turnover is further addressed through dedicated written continuity documentation that students are required to write for each subsystem at the end of each semester. Updates to "living documentation" (such as the requirements flow-down) are made periodically. All documentation is controlled through a structured revision system, inherited from CSSWE.

In order to ensure consistent student involvement across semesters (which is a management risk for all student-based projects), we engage in continuous recruiting of new students. This involves presentations at graduate seminars, fliers, emails to departmental distribution lists, and a public-domain website, which contains a dedicated page for project prospective students. Historically, the graduate projects course has attracted students from an array of departments including aerospace, electrical, and mechanical engineering, computer science, business, and the astrophysical and planetary sciences.

3.2. Project Schedule

The MinXSS top-level schedule is shown in Figure 10. For readability, most subtasks have been rolled up into summary tasks. The schedule reflects the on-going graduate projects/space hardware design class and the risk reduction provided by early (pre-award) development work.

Task durations and test sequence flow are defined by student leads and have been reviewed by LASP engineering mentors as well as the PI and Co-Is.

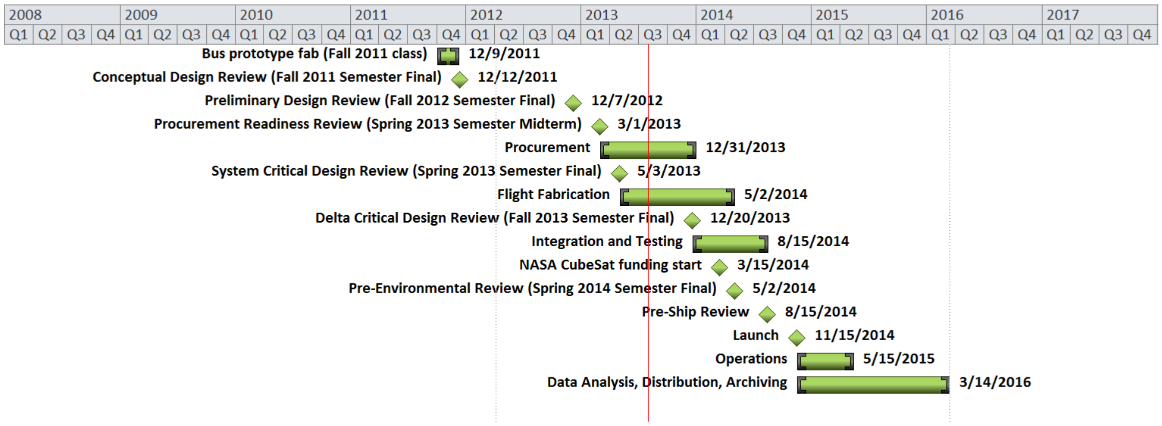
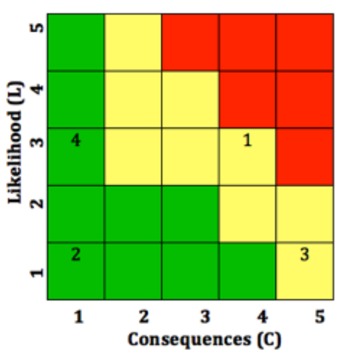


Figure 10. MinXSS Top-level Schedule. The red line in the schedule denotes August 2013.

3.3. Risk Reduction Plan

Because of their limited on-board resources, modest development budgets, and commitment to involving relatively inexperienced student teams in their design and implementation, CubeSat projects present a higher level of risk than would be acceptable for most space flight missions. However, the overall approach to continuous risk management used by larger programs applies equally well to small ones: identification of risks, categorization by likelihood and consequences, planning of mitigation strategies, and tracking of progress throughout development. This approach is taught by Professors Li and Palo in the space hardware design class, and is part of business-as-usual for the LASP mentors. The MinXSS team recognizes that some risks may have to be accepted due to the resource constraints of the program. All team members are dedicated to identifying and understanding each risk and its potential effects on the mission, and to mitigating those that have a significant probability of serious consequences.

Table 7. Top MinXSS Identified Risks.



Color code: Green = acceptable w/o further mitigation; Yellow = mitigation necessary, acceptable at launch; Red = risk drivers, aggressive mitigation need, mitigate before launch.

Rank	Risk Element and Description	Mitigation Strategy
1	ADCS is still in development and may not be ready for I&T in 2014.	Two vendors, BCT and MAI, are being considered for providing the ADCS. Regular monitoring of their development progress and performance results.
2	Deployable solar panels might fail to deploy in flight.	Robust testing on the ground in realistic environment; alternative mission operations scenario if it fails (Section 2.6).
3	Deployable antenna might fail to deploy in flight.	Strong heritage from CSSWE; robust testing on the ground in realistic environment; nylon cable degrades in UV light (self release in ~month in space).
4	Budget is low for a space flight science mission.	Use lessons learned from CubeSat CSSWE project; hire students to bridge across semesters; follow a buy-rather-than-build strategy; fabricate prototypes early; properly scope minimum mission to ensure useful science return.

Risk reduction has already been applied in three areas. First, we will buy COTS components and subsystems wherever possible, thus minimizing the amount of new design required. The key purchases include the Amptek X123, the BCT ADCS, Emcore TJ cells, and Lithium-1 Radio. Second, key MinXSS technology has already had early development. Specifically, the CubeSat Card Cage (C3) was developed in 2011, prototype units built in 2012 and 2013, flights EPS and C&DH units built in 2013, and the X123 X-ray spectrometer flew successfully on a NASA rocket in June 2012. Third, a solid working relationship has been established among Professors Li and Palo, Dr. Woods, the students in the class, and their LASP mentors. This working relationship has been in place for several years for the professional staff and in place for the 2011-2013 academic years for the students, and has shown itself to be both rewarding and cost-effective. About half of the MinXSS spring class plans to continue on for the 2013-2014 academic year.

3.4. Satellite and Environmental Test Plan

The system integration and test (I&T) for MinXSS is based on the "test as you fly" approach, successfully implemented by LASP on NASA space flight missions for over four decades as well as implemented on the CSSWE CubeSat. The MinXSS students will develop test plans and procedures and perform the environmental tests under the mentorship of LASP professionals.

Prior to integration, test procedures are developed, subsystem level testing is completed, dry runs of system level integration are performed, and a Pre-Environmental Review (PER) is held. Following the PER and spacecraft integration, the I&T flow (Figure 11) begins with the first Comprehensive Performance Test (CPT). A CPT includes testing all hardware functionality, all commands, all telemetry, and uses the same command and control software that is used for flight operations. In addition, system power is measured in all modes, the antenna and solar array deployment mechanisms are exercised, and ADCS tests are performed. The CPT is repeated throughout the I&T flow to trend and/or detect any changes in system performance.

Mass properties and spacecraft critical dimensions are measured during the P-POD fit check to verify the Cal Poly specifications. The spacecraft is installed in the P-POD and checks are made for access to connectors and remove-before-flight pin and verification of deployment switch.

Electromagnetic interference (EMI) and susceptibility testing, as would be performed for a NASA mission, is not required for CubeSats. However, it is vital to ensure that all MinXSS subsystems are compatible with each other in full operation, as done during the End to End test.

The End to End test simulates flight-like operations and the final test is performed as close to the actual flight deployment and early operations scenario as possible. The spacecraft is taken to a location approximately five miles from the LASP ground station in launch configuration, the spacecraft deployment switch is released and the spacecraft powers up in a "plugs out" configuration (without electrical GSE attached). Communication with the spacecraft is with the ground station for the entirety of the test, simulating spacecraft deployment and establishing first contact. This test verifies key system flight functionality including autonomous boot and startup, transmitter inhibit requirements, autonomous mechanism deployments, compatibility between the spacecraft and ground station, communication link margins, operations command and control software, antenna beam widths, and integrated solar array performance.

Vibration is the first environmental test, and this can be done at GSFC/WFF or at Ball Aerospace in Boulder. First the P-POD fit checks are done, then MinXSS is installed in the P-POD and vibrated to specification in all three axes. Limited functional tests are done pre- and post-vib.

The thermal vacuum (TVAC) testing will be performed in a LASP vacuum chamber with the oversight of LASP professionals. The spacecraft will be installed in the test P-POD and mounted in the chamber under a thermal hut. One survive cycle and eight operational cycles will be performed. The test approach is to "fly" the spacecraft though TVAC testing using only the ground station and RF link for command and control, allowing the student team to acquire experience and gain familiarity with the ground network and its settings, and to identify any peculiarities in the operations. A vacuum RF hut, developed and used by the CSSWE student team, allows for safe RF transmission to occur inside the vacuum chamber. An RF communication cable, power cable, and a RS232 port (connected to the spacecraft C&DH) are brought out through the vacuum chamber wall. The RS232 connection can be used, if necessary, to debug any problems while under vacuum. Each operational cycle will include power cycling, functional tests at hot and cold dwells, and practice operational passes. Orbit simulations are performed using an existing solar array simulator, with current-voltage (IV) settings that match the tested performance of the solar arrays, verifying EPS is power-positive under worst-case orbit conditions.

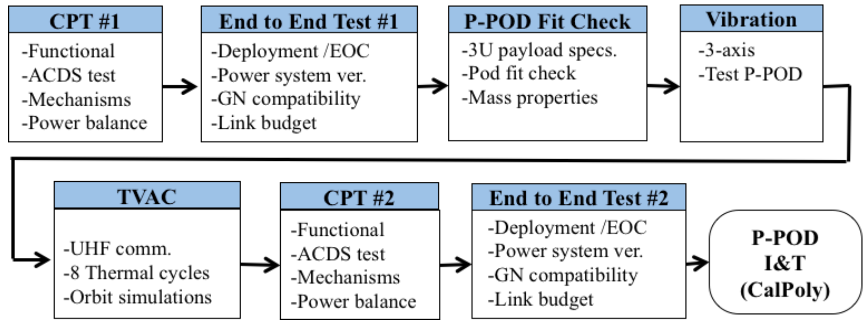


Figure 11. CubeSat MinXSS Integration and Test (I&T) Flow.

The final tests are CPT #2 and End to End Test #2. The test data are trended to look for any performance changes, and we perform final verification of system requirements prior to delivery.

3.5. Review Plan

The review plan for MinXSS follows the widely accepted practice for space flight missions, and portions of it are already implemented in the graduate projects/space hardware design class. Major reviews are shown as milestone dates in the master schedule (Figure 10). The remaining reviews are (1) Delta Critical Design Review (D-CDR) in December 2013 for improving the design of the prototype SPS/XPS and solar panels, (2) Pre-Environmental Review (PER) in May 2014, and (3) Pre-Ship Review (August 2014).

The review panel consists of peers and experts for the mission subsystems, with many of the panel members being LASP engineers who are very familiar with space hardware reviews. The reviewers provide verbal feedback during the review as well as submitting Request for Action (RFA) forms that will be formally tracked. We try to use the same reviewers throughout the life of the mission to maintain knowledge of the mission plans and past issues even though the students may change from semester to semester.

3.6. Mission Operations Plan

There are two modes of operation for MinXSS: Safe (Phoenix) Mode and Normal Operations. The Safe Mode is entered whenever MinXSS is activated (e.g., after launch) or as exit from Normal Operations. The instruments and ADCS are off in Safe Mode to enable the lowest possible power configuration. From CSSWE experience, the solar panels will eventually charge the battery enough through tumbling to activate the EPS regulators and thus turn on C&DH. C&DH startup enters Safe Mode, deploys the antenna, sends out Beacon data every minute, and then autonomously exits to Normal Operations when the battery level is high enough (SOC > 70%). Entry into Normal Operations turns on ADCS and deploys the solar panels after the first Sun acquisition. The instruments (X123, SPS, XPS) are typically on for Normal Operations but can be commanded off if power management is needed. The C&DH will autonomously transition into Safe Mode if the battery level is low (SOC < 50%).

The early orbit operations start by monitoring the Beacon data and waiting for entry into Normal Operations. This may take 1-2 days depending on battery charge level at launch. Once health and safety of the spacecraft subsystems are verified, the instruments will be activated and begin normal solar observations, which are expected to start about 1-2 weeks after launch. Based on CSSWE experience, there will be 2-6 contacts per day, and most of these contacts will be automated to download the most recent housekeeping and science data (lights-out contacts are standard procedure for our current CSSWE mission operations).

4. CubeSat Mission Implementation Requirements

The following discuss the requirements listed in NASA's Guidelines for CubeSat Proposers.

4.1. Launch and Hardware Configuration

We are working with GSFC Wallops Flight Facility (WFF) for implementing and launching MinXSS. MinXSS is designed as a standard 3U CubeSat that is compliant with the NASA/KSC Launch Services Program (LSP) Program Level Poly-Picosatellite Orbital Deployer (PPOD) and associated CubeSat Requirements Document. MinXSS will be launched under the NASA /HEOMD CubeSat Launch Initiative (CSLI).

Most of the MinXSS scientists and engineers helped with the NSF CubeSat CSSWE and thus are very familiar with the CubeSat Design Specification (CDS) and NASA LSP PPOD CubeSat requirements. No deviations or waivers from the CubeSat specification are needed for MinXSS.

4.2. Procedural Requirements

The MinXSS program has been developed for the past 2 years as a CU graduate student project, with PDR and CDR reviews already held. Being a student project, the MinXSS project has already provided and will continue to provide significant training in preparing engineers, instrument scientists, and future leaders of space flight missions.

The first opportunity for NASA participation in a MinXSS review will be its Pre-Environmental Review (PER) planned for May 2014. We will initiate early discussions with NASA CSLI program and have launch opportunities identified for the PER and PSR. Scott Schaire of GSFC WFF will represent MinXSS during the bi-weekly planning telecons with LSP.

4.3. Orbital Debris Requirements

We will select an orbit that meets the requirements of NPR8715.6 NASA Procedural Requirement for Limiting Orbital Debris. For example, a circular orbit with inclination above 40° and altitude less than 620 km will meet the requirement to reenter in less than 25 years.

4.4. Communications Licensing and Frequency Coordination

MinXSS will use CU's CubeSat UHF communication license that was first established for the CSSWE CubeSat mission.

4.5. Restrictions: Materials, Propulsion, Stored Energy, and Others

MinXSS is designed to be compliant with the LSP PPOD CubeSat Requirements Document (NASA Doc. LSP-REQ-317.01), and does not have any of the restricted materials or components listed in this document (i.e., MinXSS does not have pressurized vessel, propulsion system, radioactive material, explosive device, or hazardous material). MinXSS will be powered off after delivery and through launch and will not radiate RF until at least 45 minutes after deployment. MinXSS has RF inhibit uplink option, although that is not required as its UHF RF is only 1 W.

4.6. Implementation Assistance from NASA Centers

GSFC WFF CubeSat program (Scott Schaire, Small Satellite Projects Manager) will assist us in verifying pre-ship requirements (such as vibration test and mass properties at WFF) and will support MinXSS spacecraft integration and launch.

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