Satellite Design for Undergraduate Senior Capstone

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Dr. Hank D. Voss received his Ph.D. in Electrical Engineering from University of Illinois in 1977.He then worked for Lockheed Palo Alto Research Laboratories prior to coming to Taylor University in 1994. He is currently a Professor of Engineering and Physics at Taylor University. Some of the courses that he regularly has taught include Principles of Engineering, Intro to Electronics, Statics, Advanced Electronics, Jr. Engineering Projects, FE Review, Control Systems, Fundamentals of Space Flight Systems, Astronomy, and Sr. Capstone Sequence.

He enjoys mentoring undergraduate students in aerospace, sensors, and energy-related research projects. Some of the research areas include spacecraft nano-satellite technologies, satellite payload instrumentation, High Altitude research Platform (HARP) experiments, wave particle interactions in space, spaceflight X-ray imagers, construction and renewable energy engineering and architecture, and philosophy of science. Dr. Voss has worked as PI on many NASA, Air Force, Navy, NSF, and DOE research grants and has published over 120 scientific papers.

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Abstract

This paper demonstrates the educational value of satellite design in an engineering capstone course. Taylor University engineering capstone students participate in the Air Force Research Laboratory's (AFRL) University Nanosatellite Program (UNP) competition to design and deliver a small satellite (nanosatellite), which will accomplish a mission with real-world significance. Undergraduate educational merits and assessment are discussed and demonstrated through overwhelmingly positive feedback from alumni. The capstone course focuses on developing capable engineers with ABET a-k [1] proficiency. According to the Air Force Research Laboratory, the objective of the UNP competition is to "train tomorrow's space professionals by providing a rigorous, two-year, concept-to-flight-ready spacecraft competition for U.S. higher education institutions and to enable small satellite research and development (R&D), integration and flight test" [15]. UNP and engineering capstone design processes are also detailed. Through UNP and the senior engineering capstone class, students experience end-to-end development of a project with real-world application in the aerospace industry. The project promotes creativity and develops skilled engineers.

Figure 1: Taylor University Extremely Low Earth Orbit nanosatellite (ELEO-Sat) – background photo take from high altitude balloon at SHOT Workshop 2013

Introduction

This introduction provides a brief overview of the content of the paper. Information on the University Nanosatellite Program, the project mission, and the influence of the project on

undergraduate education is detailed in the background section. Further assessment of the educational value of the program may be found in the Assessment section. Taylor University and UNP design processes are explained in the Design section.

Background

The Extremely Low Earth Orbit nanosatellite (ELEO-Sat) (see Figure 1) is an undergraduate senior design project in an engineering capstone course at Taylor University. The project is made possible through the University Nanosatellite Program (UNP). The development of a satellite provides a hands-on learning environment that challenges students and encourages development of new skills. The benefits of participation in UNP are shared by hundreds of undergraduate and graduate students across the country.

University Nanosatellite Program

The University Nanosatellite Program (UNP) is an educational program focused on developing students by exposing them to professional engineering experiences while giving universities an opportunity to contribute to innovative scientific research projects. The aim of UNP is for "students to learn the tough lessons about satellite design by building one themselves" [3]. UNP was created to focus on three key areas, which are education, technology, and university development. This is demonstrated in each two year UNP cycle by the involvement of 10-12 universities whose individual projects exhibit advancements in education and technology.

Taylor University's involvement in the AFRL program began with TEST, a microsatellite, in UNP-3 and now continues in UNP-8 with ELEO-Sat. UNP provides many opportunities for each university and its students to glean vital, detailed knowledge about designing functional aerospace systems. The AFRL features Expert Area Teleconferences, or EATs, where field experts teach key aspects of the engineering process and subsystem design. Examples of EAT topics include configuration management, attitude determination and control, concept of operations, thermal control, and structural design.

Moreover, learning is encouraged through attendance to conferences and workshops such as the SmallSat Conference, the Student Hands On Training (SHOT) Workshop, and the CubeSat Developers' Workshop. The SHOT Workshop and SmallSat Conference were held during the summer of 2013; more than half of the Taylor University team attended one or both. The focus of the SHOT workshop is to teach small teams from each university the skills necessary to assemble a balloon satellite, which is a low-level satellite prototype for a high altitude balloon launch. The SmallSat conference introduced students to new small satellite technology and developments. Those who attended received an excellent learning experience regardless of their engineering background. The next CubeSat Developers' Workshop will be in April 2014.

UNP also provides mentorship for each team. Each UNP team is assigned a point of contact (PoC) at the AFRL. The point of contact can provide technical guidance for the design process and connect a team with expert contacts for further assistance. Contacts provided by a PoC sometimes become additional mentors on the project.

Mission Overview

The University Nanosatellite Program equips students to accomplish a satellite mission, (see Figure 2). The multidisciplinary project may be summarized in a singular mission statement.
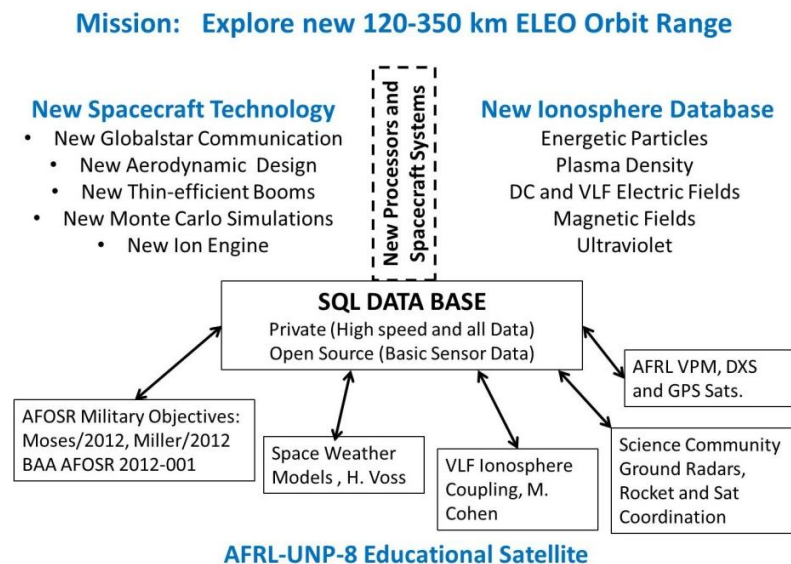

Figure 2: ELEO-Sat Mission statement and objectives diagram

The primary mission of ELEO-Sat is to explore the uncharted 120-350 km Extremely Low Earth Orbit (ELEO) region of the ionosphere. As laid out in Figure 2, the mission may be broken down into the scientific and technical objectives of developing an open source database of in-situ wave, particle, and plasma ionospheric measurements and demonstrating new, innovative spacecraft technologies. The Air Force Office of Scientific Research (AFOSR) has expressed great interest in ionospheric science [9] [14]. The ionosphere has been studied from higher LEO orbits (160-2000 km) and from vertical rocket profiles; however, few in-situ measurements have been taken. The in-situ measurements from ELEO-Sat may help researchers to better understand phenomena such as VLF-LEP coupling, plasma dynamics, VLF transionospheric propagation/attenuation, and many others (see Figure 3). Additionally, ELEO-Sat complements the current AFRL DSX and VPM missions.
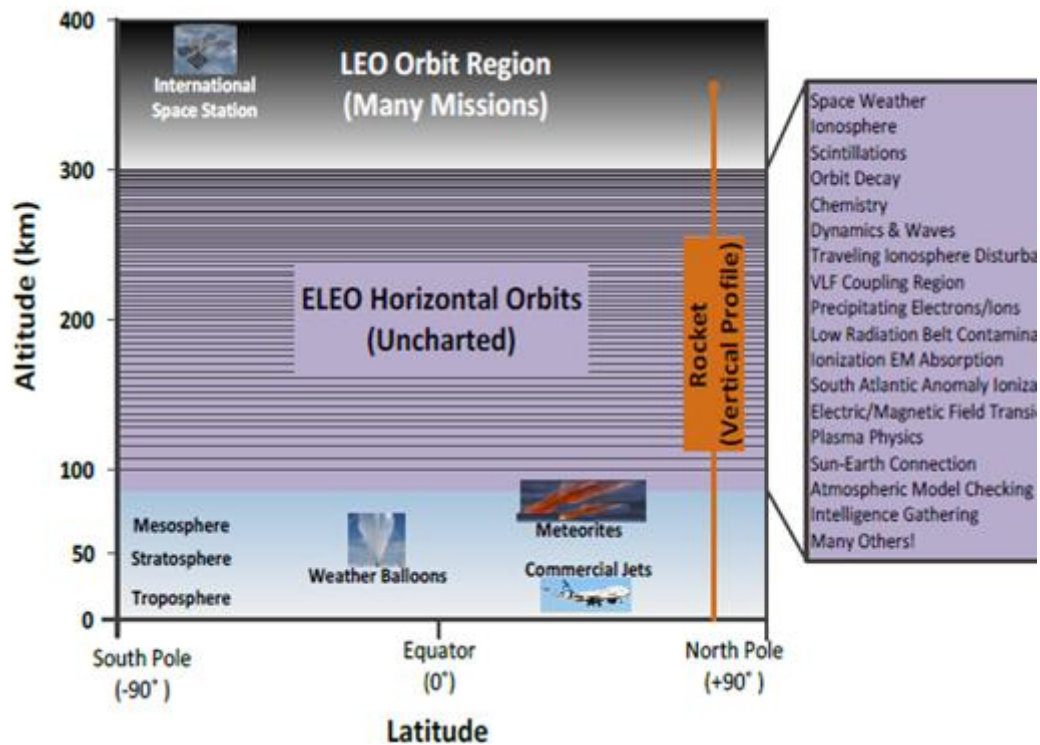
Figure 3: Diagram of mission location

As a part of its exploratory mission, ELEO-Sat will demonstrate new, innovative technologies for Low Earth Orbit (LEO), 160-2000 km, satellites. Technology objectives connect to AFOSR relevance [14]. A Globalstar satellite-to-satellite communication link will allow global throughput for LEO orbit satellites and potentially allow continuous command capability. The new communications link will be flight tested for the first time in spring 2014 aboard TSAT and GEARR-Sat, predecessors of ELEO-Sat. Uniquely, ELEO-Sat will rely primarily on passive attitude control, including a gravity gradient and an aerodynamic control loop, and will utilize an aerodynamic form factor to increase its lifetime in ELEO, where drag forces are high [8]. In-house developed Monte Carlo simulations will empower preflight analysis of drag effects [8] and performance of a new ion engine.

The objective of education (shown at the base of Figure 2) expresses the educational foundation of UNP. The educational experience of building a nanosatellite is one of the major underlying purposes set forth by the UNP. Thus, the experience greatly contributes to student learning.

Undergraduate Educational Merits

The ELEO-Sat project provides a unique opportunity for student learning through a real-world design experience. At the end of the two year UNP cycle students supply a satellite to the Air Force Research Laboratories. Hands on satellite development helps students develop important career skills such as teamwork, systems engineering, and integration. Students learn

the importance of deadlines and scheduling throughout the design and development process. A high expectation level encourages students to produce quality work and to present it with competency at design reviews with the Air Force and industry professionals. The process provides insight into the professional world and teaches students to develop individual subsystems within a team.

Team members come from a wide range of disciplines. Students from each of Taylor University's engineering majors, which include Engineering Physics, Computer Engineering, Environmental Engineering, and Systems Engineering, participate in the same senior capstone course. Junior and underclassman engineering students are also involved in the project, working on smaller subsystems or tasks, in order to mitigate risk presented by student turnover upon graduation. Students in majors including Mathematics, Physics, Business, Accounting, Elementary Education, and Computer Science also participate voluntarily in the senior engineering project under the leadership of the faculty and engineering students. For example, an undergraduate mathematician developed and calibrated Monte Carlo simulations of free-molecular aerodynamics to determine drag effects in ELEO orbits. An example of non-technical involvement is business students who organized events to promote campus awareness of ELEO-Sat. Moreover, the senior capstone course involves local high school students considering STEM careers through outreach programming including participation in high altitude balloon projects. Similarly, the project provides outreach opportunities to local elementary schools, using space science curriculums developed by Taylor University elementary education majors. Working on projects like ELEO-Sat equips students from many disciplines with skills they need for the future. Collaboration between non-capstone students, professors, and engineering students benefits student learning as a whole.

Design Process

The design process in the engineering capstone course facilitates end-to-end design and traces ABET a-k objectives. Figure 4, a diagram adapted from Ford-Coulston 2008, illustrates how the engineering capstone course connects the ABET a-k objectives [1], listed below, to an intentional, directed, thoughtful, and sustainable design process. The curriculum emphasizes each of the four design processes at different points in the course as indicated by the associated dates. The multiple node lines in the decagon represent many feedback and discussion pathways. The black abbreviations underneath the process headings indicate documents required within each phase and the highlighted outcomes indicate ABET a-k objectives linked to each process and stage of the design. Subsequent subsections in the Design Process section indicate connections to the Figure 4 design process by identifying corners of the decagon e.g. "Figure 4 – 2 Brainstorming, Research, Scope."
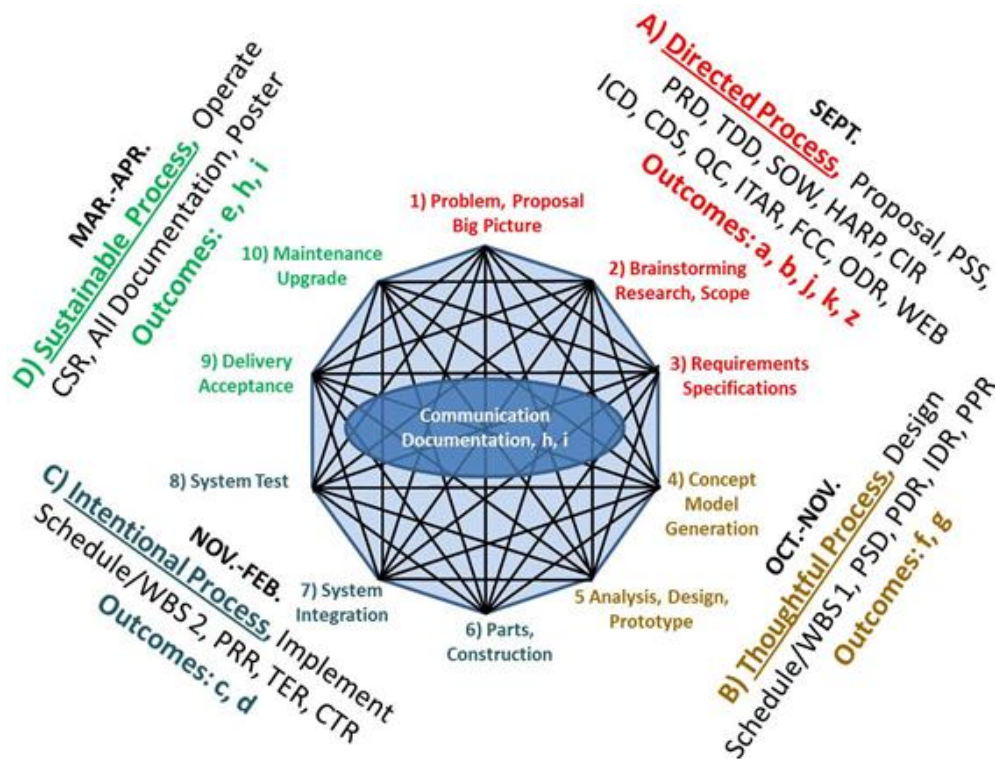
Figure 4: Capstone design process

ABET A-K Objectives

Students are expected to possess or develop:

a.   an ability to apply knowledge of mathematics, science and engineering
b.   an ability to design and conduct experiments, as well as to analyze and interpret data
c.   an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
d.   an ability to function on multidisciplinary teams
e.   an ability to identify, formulate, and solve engineering problems
f.   an understanding of professional and ethical responsibility
g.   an ability to communicate effectively (3g1 orally, 3g2 written)
h.   the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
i.   a recognition of the need for, and an ability to engage in life-long learning
j.   a knowledge of contemporary issues
k.   an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Additionally, the design process is guided by UNP standards for design reviews. Figure 5 and

6, below, illustrate the electrical and mechanical design processes, respectively [13]. Review deliverables, e.g. concept, breadboard, brass board, are expected at the reviews indicated, e.g. SRR, PDR, CDR.

Completed by: SRR   PDR   CDR

Concept
- What is the board's purpose?
- What components are needed?
- Will the board meet instrument/subsystem requirements?

Breadboard
- Implements primary function of PCB
- Built from PC Board or plug-in kits

Brass Board
- Uses commercial parts
- Laid out and populated PCB
- Does not need to be in flight PCB format
- Designed for testing and debugging

Completed by: Layout by PQR   Tested by FCR   Flight Build Review

Silver Board
- PCB laid out in flight footprint
- Flight parts and packages
- Thermal testing (essential prior to satellite thermal testing)
- Configuration Management

Gold Board
- Final layout and population
- Conformal coated
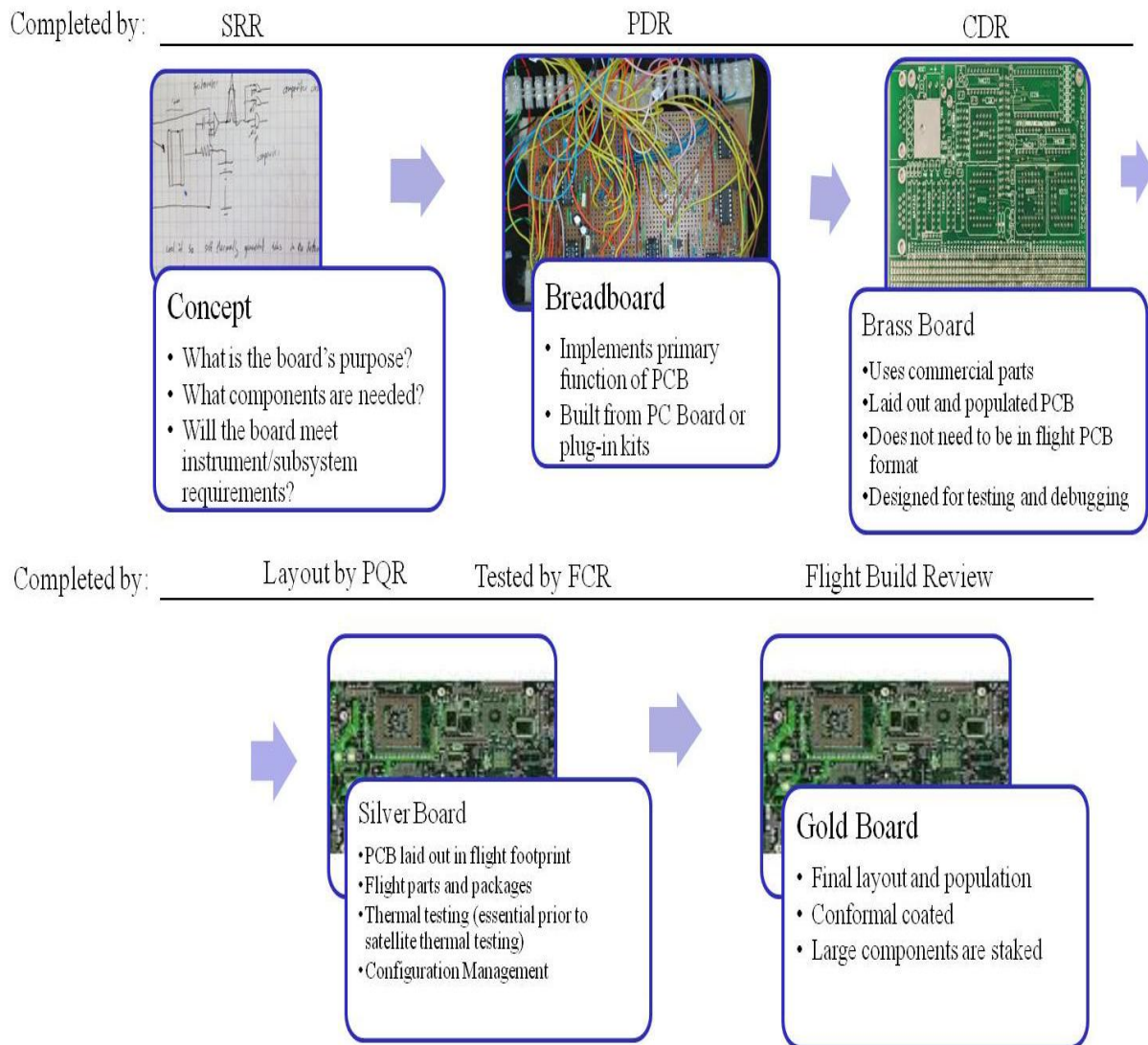- Large components are staked
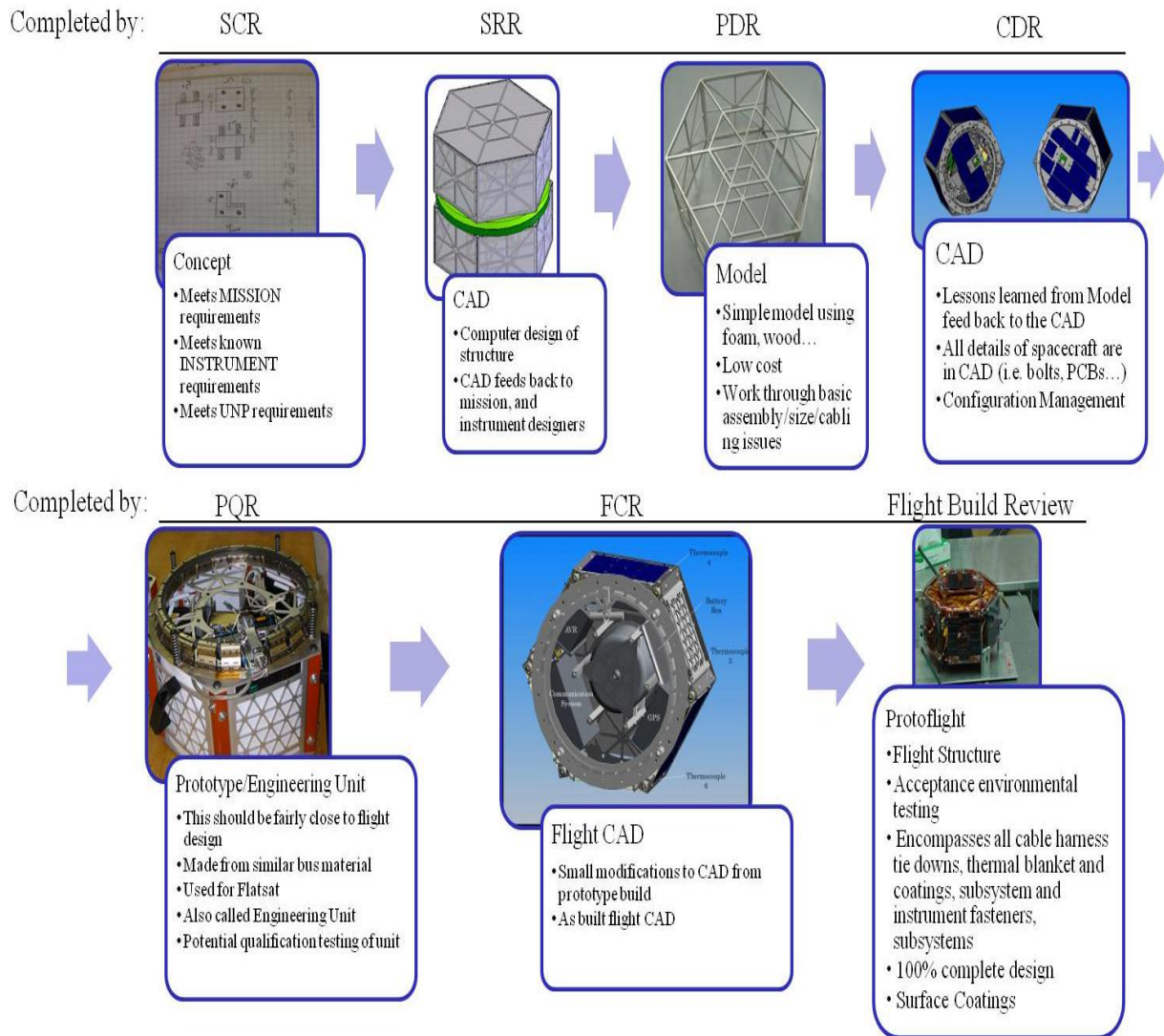
Figure 5: UNP Electrical design process

Figure 6: UNP Mechanical design process

UNP review deliverables include required documentation. Deliverables for the Flight Competition Review (FCR) include:

- Assembly Procedures
- Block Diagrams
- CAD of Spacecraft
- Concept of Operations
- Data Budget
- Document Tree
- EMC/EMI Mitigation Design
- Experiment Plan
- Ground Support Design
- Interface Control Documents

- Personnel Budget
- Power Budget
- Press Related Information
- Pressure Profile
- Proof of Licensing
- Protection Plan
- Quad Chart
- Radiation Mitigation Design
- Requirements Verification Matrix
- Schedule

- Link Budget
- Mass Budget
- Master Equipment List
- Materials List
- Mechanical Drawing Package
- Mission Overview

- Silver Board Test Results
- Software
- Structural Analysis
- System Functional Test Results
- Thermal Analysis

The UNP User Guide describes the documentation deliverables in depth [12]. Work on the design deliverables is expounded upon in subsequent subsections of the design process.

Design Challenges

In order to achieve mission success, students must address real-world spacecraft design challenges. The multidisciplinary nature of the design challenges is one of the reasons why a multidisciplinary team is so important. Spacecraft design requires electrical, electromagnetic, mechanical, thermal, embedded systems, and systems engineering skills.

The wide variety of environmental factors is among the most difficult and critical challenge to overcome. Radiative heat transfer and internal heat production set the nominal thermal environment inside the spacecraft, which must be maintained within operating temperature ranges. The satellite must additionally be able to survive the high intensity vibration and stress experienced in the launch environment. Students design to wide margins to account for uncertainty. For example, since the satellite will be a secondary payload, the design must address uncertainty in launch date and orbit, which are not guaranteed and may greatly influence the ambient thermal environment and battery charging cycle. Moreover uncertainty in the launch date brings new factors into play such as mechanism creep. The design must also account for the high drag forces experienced in low earth orbit, which may decrease satellite lifetime and cause spacecraft rotation.

Many other design factors are considered in satellite design. Subsystems must be spatially allocated to eliminate mechanical crowding, simplify cable routing, and mitigate the risk of electromagnetic interference between subsystems. Other factors are captured in design budgets (see documentation requirements for FCR above). Students respond to uncertainty in design budgets by providing margins of at least 20% in the early design phases.

Spacecraft Overview

The satellite payload utilizes three primary instruments, which are supported by secondary instruments and the spacecraft bus. Measurements from the three primary spacecraft instruments will be compared to investigate the interactions between waves, particles, and plasmas in the ELEO region. Figures 7 and 8 provide illustrations of the system design that is discussed briefly below.
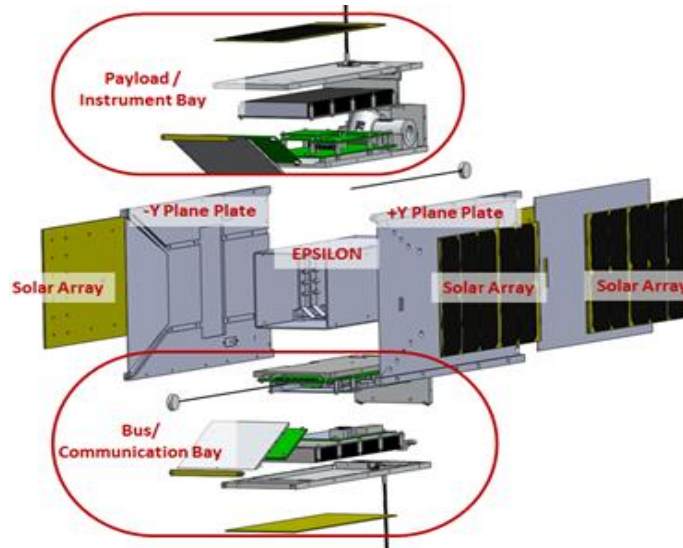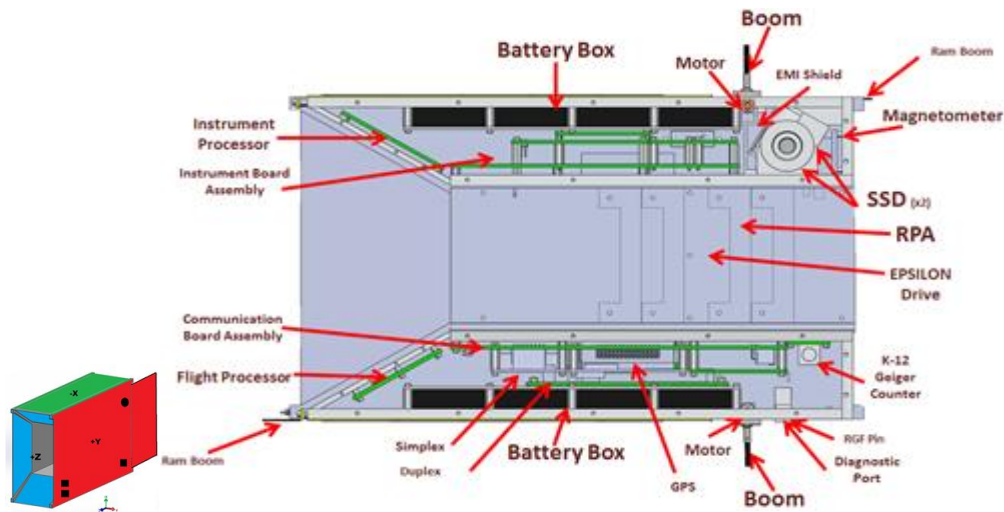
Figure 7: Spacecraft system exploded view

Figure 8: Spacecraft system diagram with labels

Electric fields in the range DC-30kHz will be measured utilizing four deployable booms, two that will act as a gravity gradient, orienting perpendicularly to the earth, and two that will point in parallel and antiparallel directions relative to the motion of the spacecraft. The voltage differential between the booms on each axis will be used to determine the magnitude and direction of the in-situ electric fields. Measuring the electric field at points distant from the spacecraft will reduce the risk of electromagnetic interference (EMI) and potentially increase instrument resolution.

Two solid state detector (SSD) telescopes, each containing two detectors in coincidence, will be used to measure the pitch angle distribution of particles precipitated from the radiation belts. The SSD array will count electrons and ions in the energy range 30keV-1MeV, separating

counts from each into bins by energy level. The detectors will be aligned on an optical bench (see Figure 9) at 90˚ and 30˚ relative to the L=2 through L=3 magnetic field lines. The solid state detectors are isolated behind an EMI shield to mitigate EMI risk.
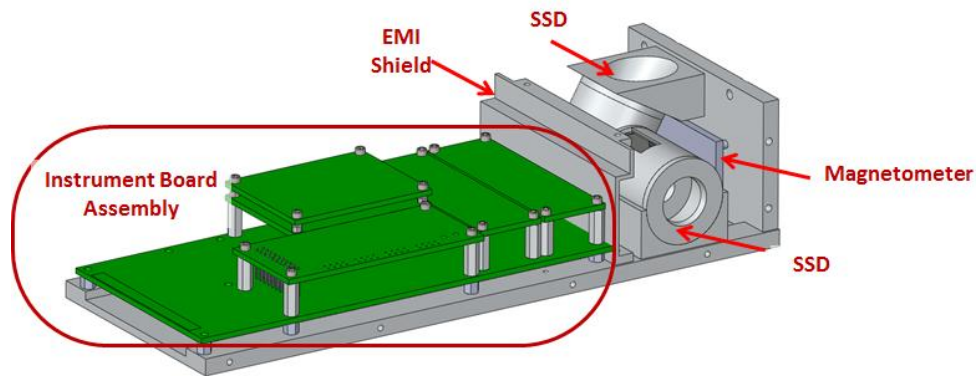

Figure 9: Instrument optical bench

The density and temperature of plasma will be measured using two Langmuir Probes. The probes will be mounted on the exterior of the spacecraft, parallel to the direction of motion. The plasma temperature is proportional to the slope of the I-V curve, generated by sweeping the probe voltage, and the plasma density is proportional to the current at a constant bias voltage.

ELEO-Sat will utilize secondary scientific instruments that are not considered part of the payload, including a 3-axis magnetometer, ultraviolet photodiodes, and a GPS unit. The secondary instruments are necessary to support the primary scientific mission. The magnetometer, photodiodes, and GPS are used to gather valuable information about position and pointing direction for the Attitude Determination and Control System (ADCS).

The spacecraft bus supports the spacecraft instruments so that the primary mission can be accomplished. The Attitude Determination and Control System (ADCS), described briefly above, will orient the spacecraft instruments in the proper pointing direction through a combination of both an aerodynamic control loop and a 3-axis magnetorquer. Power will be supplied from solar arrays and batteries by the Electrical Power System (EPS), which will additionally provide watchdogs to mitigate the risk of electrical power failure. Command and Data Handling (CDH) will manage the spacecraft operational modes and data collection. On-orbit data downlink and command uplink will be facilitated by the Communications System.

Problem Identification

Figure 4 – 1-2 Problem, Proposal, Big Picture Brainstorming, Research, Scope

Mission scope is identified in the initial proposal; however, the scope for each individual subsystem must be defined. Some advanced science and engineering topics are new to many incoming capstone students, so it is necessary for each to develop a foundation in the subject

matter before identifying subsystem scope in a Project Scope Statement. The learning process is accomplished through both student interaction with the Primary Investigator (PI) and independent research. Evaluation of Project Scope Statement documents is conducted by the PI and other supervising faculty.

Requirements Analysis

Figure 4 – 3 Requirements Specification

After students have gained a thorough understanding of their projects, the student scopes are broken down into requirements. Students use Ford-Coulston, *Design for Electrical and Computer Engineers* as a primary tool for learning requirements analysis. IEEE std. 1233-1998 states that requirements must be abstract, verifiable, unambiguous and traceable [4]. Ford-Coulston adds that requirements must be realistic [4]. Although the literature is intended specifically for electrical and computer engineers, the design process is relevant to each of the engineering disciplines represented on the project. The UNP User Guide specifies that requirements should be captured in a Requirements Verification Matrix (RVM) [12]. The flow-down of requirements in the RVM (see Figure 10) ensures that all requirements are mission relevant.

1) Mission Objectives
2) Mission Success Criteria
3) Measurement Requirements
4) Pointing Requirements
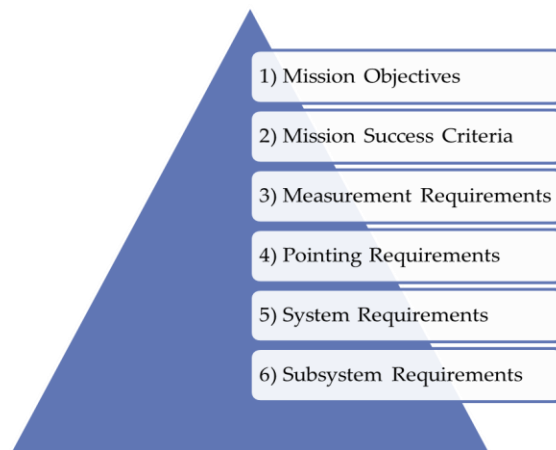5) System Requirements
6) Subsystem Requirements

Figure 10: Requirements flow-down

The flow-down of the requirements is captured in sources either from within the RVM or from outside documents (see Table 1). UNP satellites must additionally comply with UNP and California Polytechnic State University (Cal Poly) requirements (see Table 2). Each requirement is initially assigned one of four verification methods: inspection, analysis, demonstration, and test [6]. Test and analysis verifications are given short descriptions in the RVM and specific procedures are determined at the beginning of testing phases.

Ref	Requirement	Source	Verification

ThEEF-1	ThEEF shall measure E-fields over the frequencies DC-30kHz	Instrument requirements - data budget document	Test: calibration
ThEEF-2	ThEEF shall have an equivalent noise input of less than 1 mV/m	Instrument requirements - data budget document	Test: calibration
ThEEF-3	ThEEF Will measure E-fields with magnitudes up to 2.5 V/m	Instrument requirements - data budget document	Demonstration
ThEEF-4	ThEEF shall measure E-fields on two axes	Mission Overview	Inspection

Table 1: RVM Sample - ThEEF Instrument Subsystem Requirements

Ref	Requirement	Source	Verification
MS-1	The SmallSat shall be designed to withstand the launch and on-orbit environments of the launch vehicle without failure, leaking fluids, or releasing anything.	UNP-2, CP-7, CP-8	Test: vibration table, thermal vacuum
MS-2	The SV shall be designed using the MAC curve in Figure 7 in section 6.3.1 of the NS-8 User Guide	UNP-3	Test: vibration table, thermal vacuum
MS-3	Factor of safety to be used are 2.0 for yield and 2.6 for ultimate for structural design and analysis	UNP-4	Analysis: SolidWorks simulation
MS-4	The SV volume shall depressurize safely at a rate of 0.5 psi/sec	UNP-5 CP-4, CP-5	Test: thermal vacuum
MS-5	The SmallSat shall be designed to withstand the launch vehicle shock environment as shown in Table A and Figure A (Table A and Figure A are available in actual RVM)	UNP-6	Test: vibration table

Table 2: RVM Sample - Mechanical chassis requirements

Concept Generation

Figure 4 – 4 Concept Model Generation

Requirements are synthesized into design concepts, which are most commonly represented on a block diagram level. Figure 11 exhibits a student's concept for an instrument processor subsystem. The appropriateness of project scope, requirements, and concepts are assessed by the PI, other supervising faculty, and peers in concept reviews.
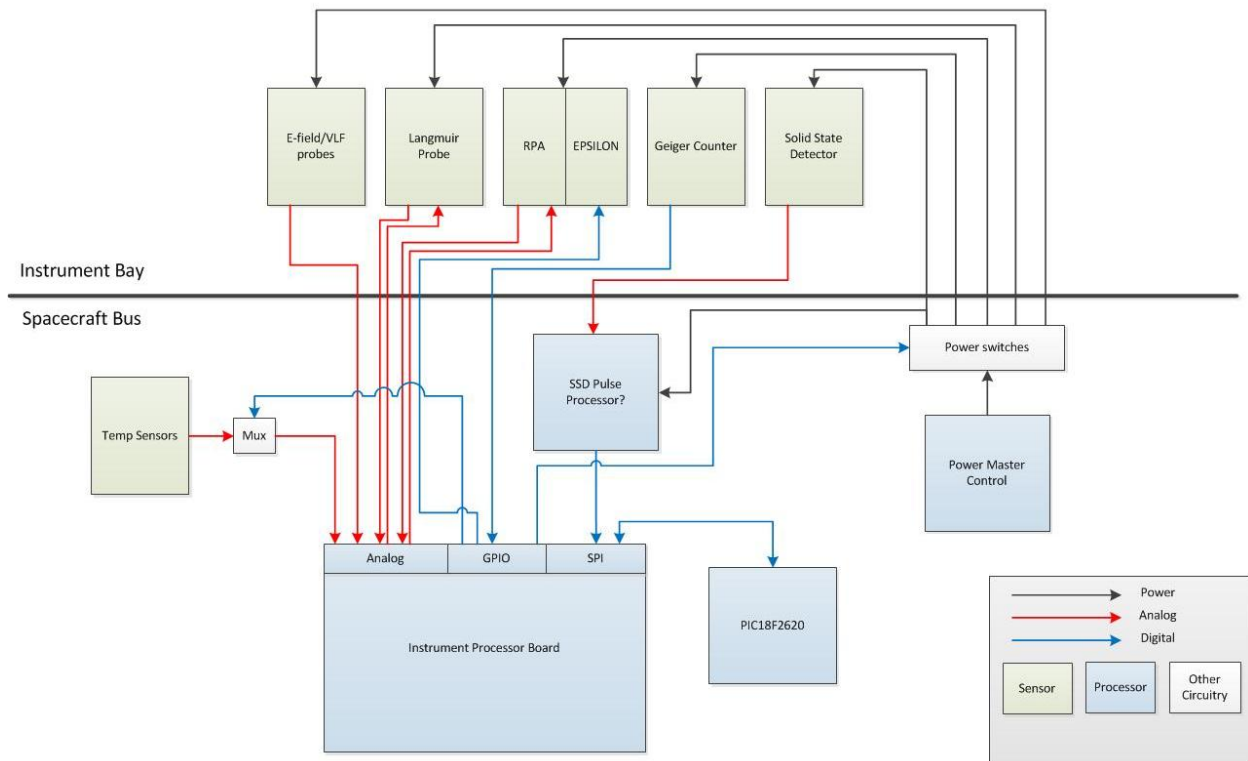

Figure 11: Instrument processor subsystem concept

Evaluation of real-world design tradeoffs is critical for determining which concepts will be implemented in the design phase. Technical Readiness Level (TRL) and risk are two of the primary judging criteria in UNP; thus, design trade-offs are evaluated accordingly using TRL charts (see Figure 12) and Likelihood-Consequence (L-C) Charts (see Figure 13) [13]. TRL charts indicate overall system and subsystem progress measured by readiness of review deliverables. Moreover, TRL charts may be used to identify critical paths for project work. Subsequently, design trade-offs are evaluated on the basis of adherence to the critical path.

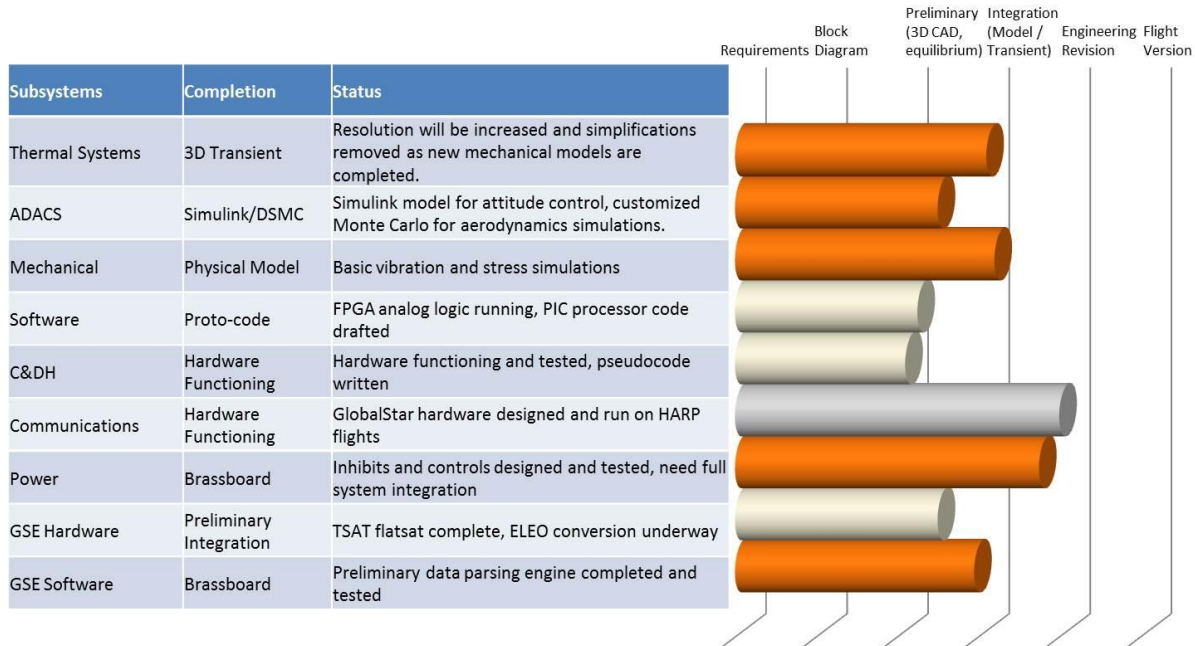| Subsystems	Completion	Status
Thermal Systems	3D Transient	Resolution will be increased and simplifications removed as new mechanical models are completed.
ADACS	Simulink/DSMC	Simulink model for attitude control, customized Monte Carlo for aerodynamics simulations.
Mechanical	Physical Model	Basic vibration and stress simulations
Software	Proto-code	FPGA analog logic running, PIC processor code drafted
C&DH	Hardware Functioning	Hardware functioning and tested, pseudocode written
Communications	Hardware Functioning	GlobalStar hardware designed and run on HARP flights
Power	Brassboard	Inhibits and controls designed and tested, need full system integration
GSE Hardware	Preliminary Integration	TSAT flatsat complete, ELEO conversion underway
GSE Software	Brassboard	Preliminary data parsing engine completed and tested

Figure 12: Bus systems TRL Chart from Preliminary Design Review

An L-C Chart displays how the likelihood (y-axis) of a risk and the resulting consequences (x-axis) relate to the overall risk (color, green is low risk). Figure 13 also identifies the design risks corresponding to numbers in the L-C Chart. The expectation is that risks are unambiguously identified in a manner understandable to reviewers who may not be familiar with the project.

Figure 13: L-C Chart for 3U to 6U size Design change from Critical Design Review

L-C and TRL charts encourage thoughtful design and demonstrate effective preparation to UNP judges. Other methods of evaluation are used as appropriate. For example, along with L-

C Chart analysis (see Figure 13), students used a cost/benefit analysis when evaluating a design change from a 3U size (10x10x34cm) to a 6U size (10x20x34cm) [2] (see Figure 14).
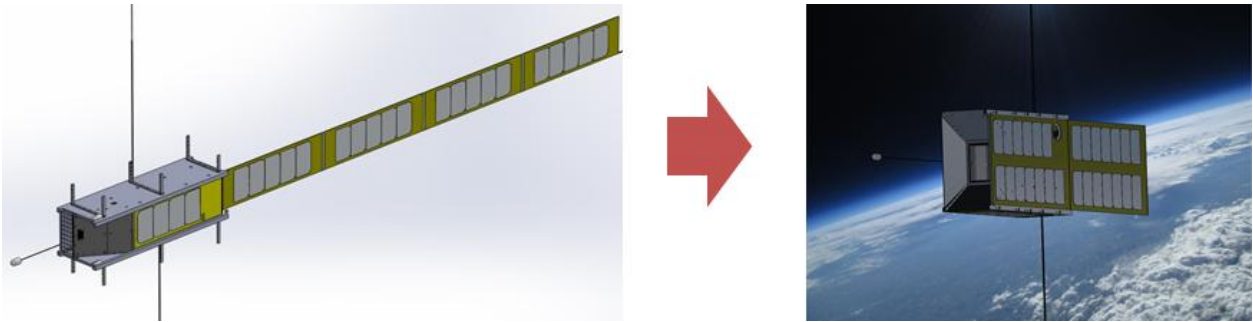

Figure 14: 3U to 6U Design Change Graphic from Critical Design Review

Design

Figure 4 – 5 Design, Prototype, Analysis

When concepts are approved, students begin the iterative process of design, prototype, and analysis. Applying undergraduate learning to hands-on experience is one of the most valuable elements of UNP. Students apply a variety of tools to the design of their subsystems. Mechanical designs are implemented in SolidWorks and MatLab. SolidWorks Simulation Premium is capable of performing multiple analyses for required deliverables including pressure profiles, static loading, and vibration simulations. Figure 15 illustrates the exaggerated results of mode frequency testing.

Frequency Modes:
1) 3.9167 Hz
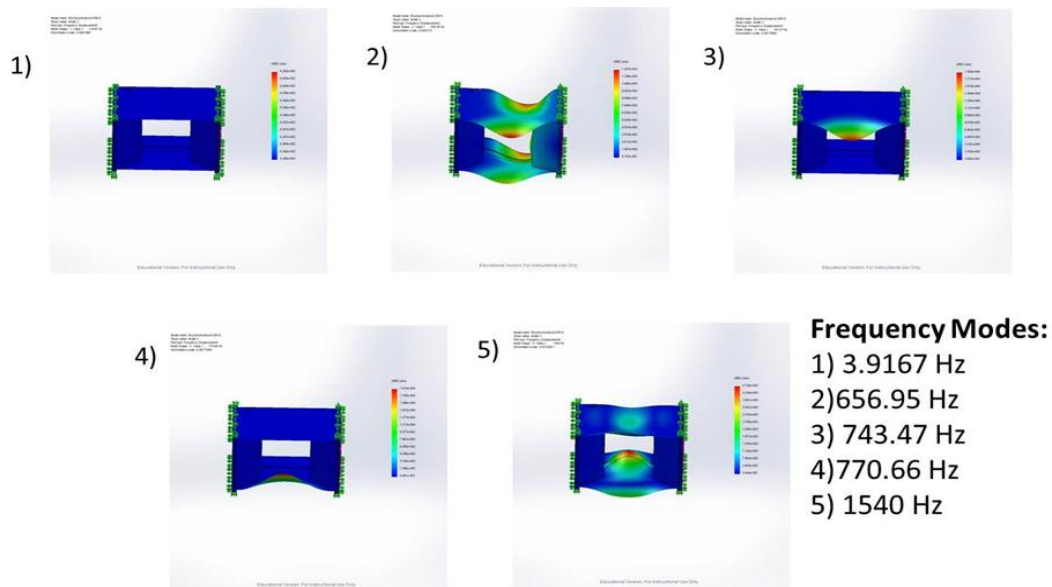2) 656.95 Hz
3) 743.47 Hz
4) 770.66 Hz
5) 1540 Hz

Figure 15: SolidWorks analysis of chassis vibration modes (Exaggerated)

SolidWorks is also used for 10+ node thermal analysis. Thermal models with fewer than

10 nodes are implemented in MatLab Simulink because it allows students to fine tune assumptions used in the analysis. For the same reason, lower node Simulink models are used to verify higher node SolidWorks models. MatLab has other useful plugins including the CubeSat Toolbox which was used to determine solar power gathered over a typical ELEO orbit (see figure 16).

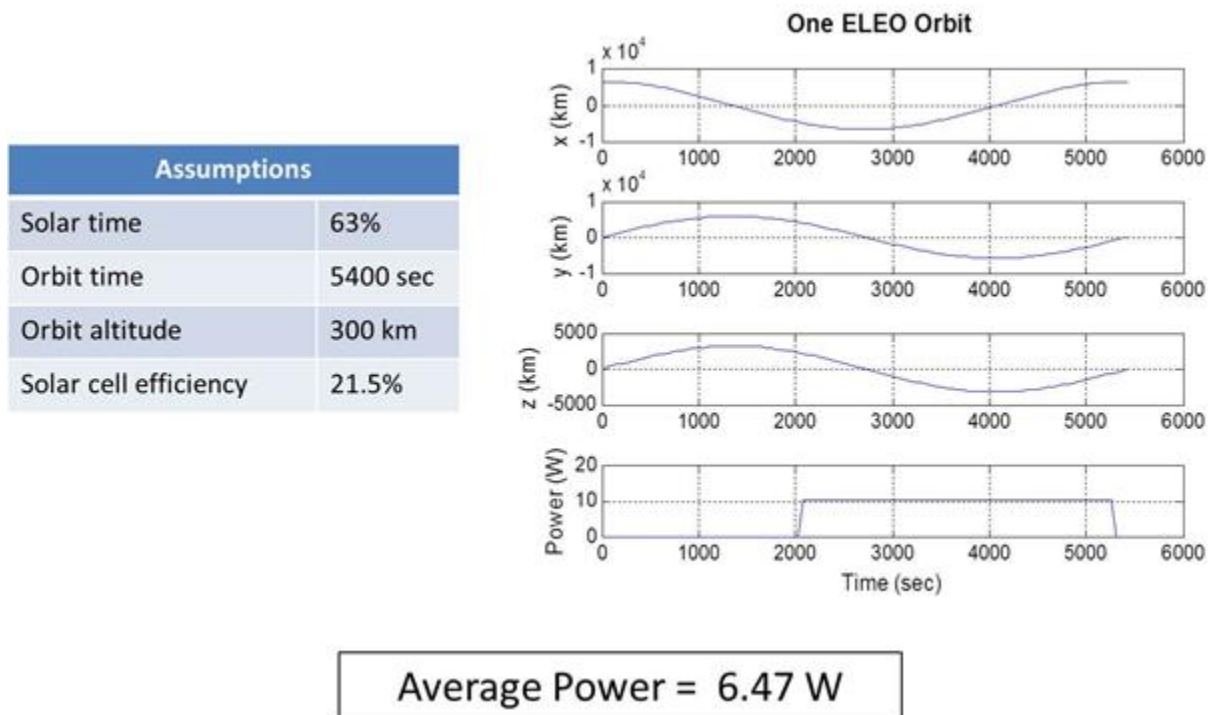| Assumptions	
Solar time	63%
Orbit time	5400 sec
Orbit altitude	300 km
Solar cell efficiency	21.5%

Average Power = 6.47 W

Figure 16: Solar power simulation in MatLab CubeSat Toolbox

After initial analysis in SolidWorks, mechanical models are fabricated on a BFD 3DTouch 3D-printer. Prototyping the mechanical model facilitates development of assembly procedures and cable harnessing (see Figure 17).
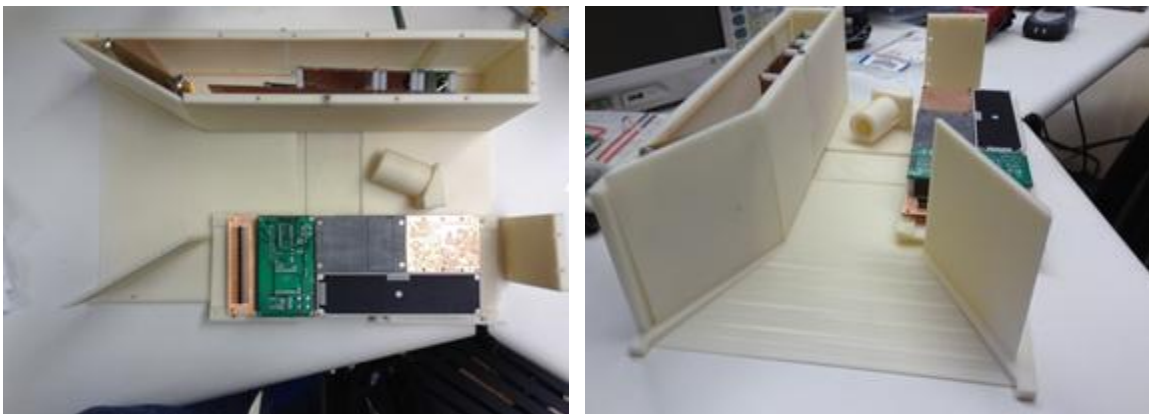

Figure 17: 3-D printed chassis

Electrical designs are tested on breadboards and analyzed in LTspice or PSpice. Success

with preliminary analysis and testing is channeled into schematic and board development in Eagle CAD. Printed circuit boards (PCBs) are subsequently fabricated on an LKPF ProtoMat S63 PC Mill. Figure 18 exhibits a design (left) and prototype (right) of the instrument processor board, which was developed from the concept in Figure 11.
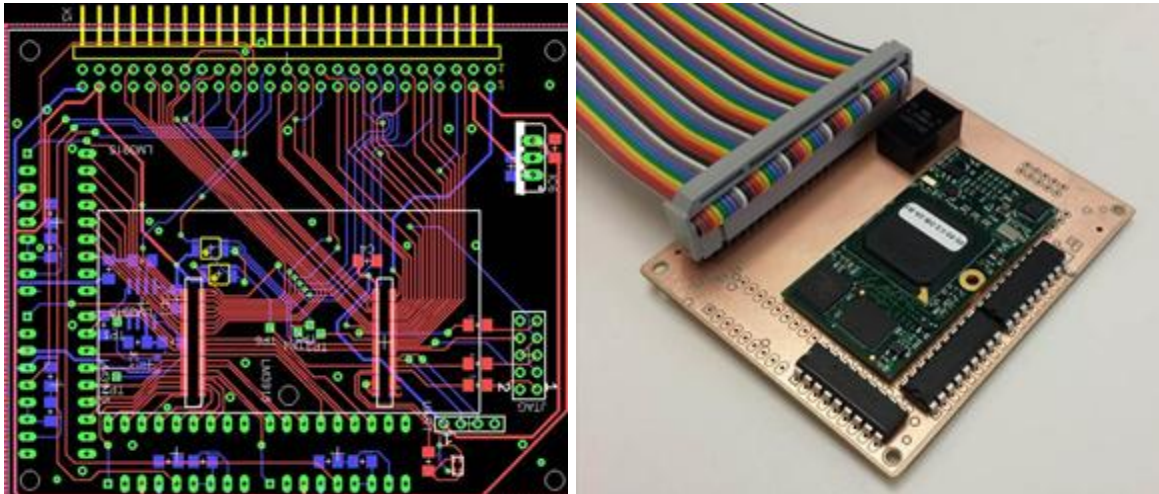

Figure 18: Instrument Processor Eagle CAD Layout and PCB

Electrical brass boards are then tested and calibrated. Figure 19 (left) exhibits an oscilloscope screen shot of the response of a Solid State Detector (SSD) to a calibration pulse. Similarly, Figure 19 (right) displays calibration curves of the VLF search coil in response to an applied magnetic field.
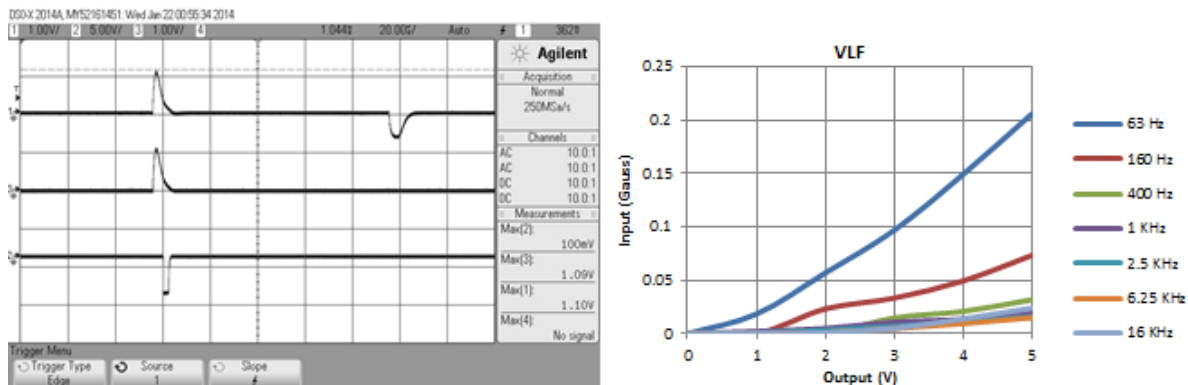

Figure 19: SSD Pulse Scope Shot (Left) and VLF Search Coil Calibration Curves (Right)

System Integration

Figure 4 – 6-8 Parts, Construction, System Integration, System Test

After all subsystems are designed, they must be integrated into a functioning system. Interfaces are the most important place to improve a design and the easiest place to make

mistakes. Students learn many of their lessons the hard way on interfacing. The High Altitude Research Platform (HARP) is Taylor University's high altitude balloon program and a primary testing method for ELEO-Sat (see Figure 20). The near-space environment that HARP balloons encounter is similar to the thermal-vacuum and vibration testing that the satellite will undergo before acceptance. In-house tools, including a 3D-printer, a PC-mill, and a laser cutter are utilized for fabrication of spacecraft prototypes. By participating in HARP launches, students learn project engineering and communication skills through team integration and assembly.
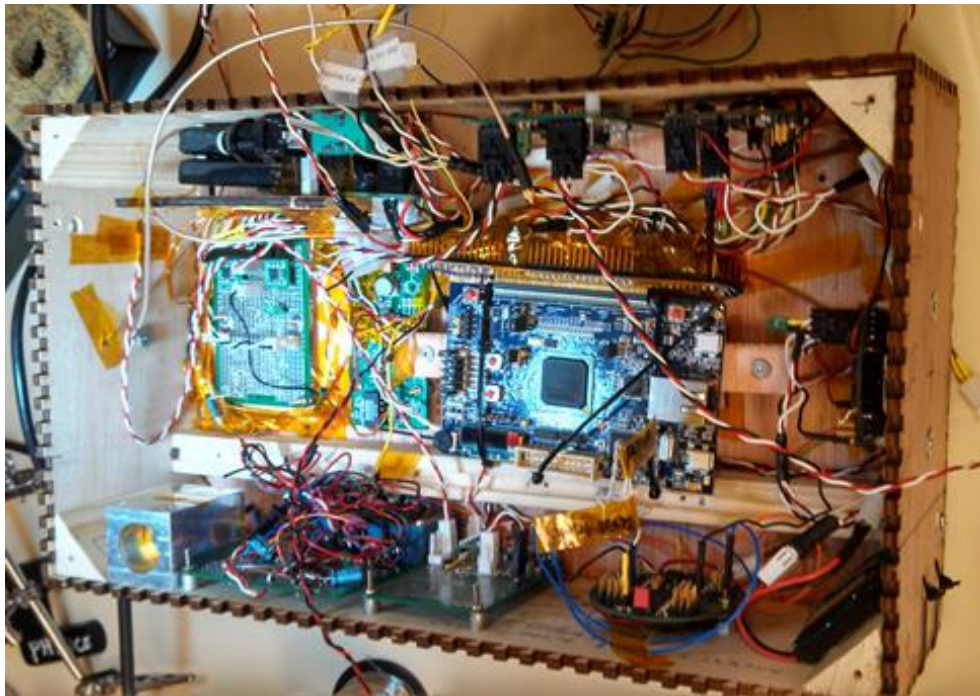

Figure 20: Integrated ELEO-Sat balloon satellite.

Even though each sub system is fully functioning in bench testing phases, bringing them together reveals many undiscovered problems, not only for individual subsystems but also for the overall system. These problems, both electrical and mechanical, are only discovered once everything is assembled.

Delivery & Maintenance

Figure 4 – 9-10 Delivery, Acceptance, Maintenance, Upgrade

If the team successfully completes the Flight Competition Review (FCR) it will proceed to the next stage of UNP, where the team will continue the development of the satellite alongside the AFRL. The second phase of the program continues until the satellite is flight ready. Maintenance and upgrade, if necessary, occur after the acceptance of the satellite.

Assessment

Establishing an efficient design process through the capstone class requires assessment of the program to determine what works and what does not. A good capstone class encourages vision and challenge while capturing imagination. Students should be encouraged, but much is expected from them. When there is strong team spirit, trust, and vision in a capstone project, the potential for learning is high. Figure 4 helps define the ABET outcomes and the design process sequence that is used for development of each student's subassemblies and the integration of the complete and tested satellite. It can be very hard for students to appreciate the many feedback and feed-forward lines in the classic design process between decagon vertices and the ABET outcomes a-k (see Figure 4). The ABET outcomes are reinforced and developed continuously throughout the full design cycle.

The formal student documents required for evaluation and assessment include the following: POP (Project Big Picture Overview Proposal), PSS (Project Scope Statement), PRD (Product Requirements Document), TDD (Team Definition Document), SOW (Statement of Work/Work Breakdown), NAS (NASA CubeSat Requirement Documents), PSD (Product Specification Document), PDR (Preliminary Design Document & Review), CDR (Critical Design Document & Review), PPD (Pre-Procurement Review, WBS, Schedule), ASEE1 (Submit ASEE Draft Papers), HARP (High Altitude Balloon Research Platform), ASEE2 (Submit final Papers and Posters), SCR (ELEO-Sat System Concept Review), SRR (ELEO-Sat Systems Requirements Review), and FINAL (Final Notebook and Documentation).

Also included in assessment is individual progress on the hardware subsystems, software architectures, CAD mechanical drawings, thermal and testing methodologies, and overall design process. Project management, Work Breakdown Structure, Bill of Materials, schedules, and overall status were also assessed by faculty members in individual meetings throughout each semester.

The Capstone class faculty assessment was consistent with the student assessment questionnaire. The student assessments to the question "Did the Capstone experience open your eyes and abilities to better implement the full design process and accomplish many of the ABET objectives A through K?", resulted in 86% students with the highest mark ("Strongly Agree") and 14% with a reply "Agree" giving a score of 3.9 out of 4.0 scale. A student (S1) comment associated with this question is, "I learned tons about timing, prototyping, testing failure analysis, project management, and much more".

Assessment of the quality of a national level project with documentation and lab work was excellent. This is also similar to what the students reported in the questionnaire assignment. A second question received a 3.7 score, from 71% "Strongly Agree" response and 29% "Agree" response. The question was, "Do you value that TSAT and ELEO-Sat are national level projects with interaction with other universities (ASEE, UNP), students, industry (ITT Aerospace), NASA and the Air Force and undertake important research?" Student comments (S4, S6, and S7) stated the following: "This project, and its level of recognition, means a lot to me. I would not

feel I was getting my money's worth in the engineering curriculum if we did not have this sort of project, and I may have considered transferring schools", "This experience has been priceless to put on a resume and learn what industry is like. I hope more students have this opportunity.", and "everyone seemed shocked".

Grading for the capstone course is based on each student's weekly status and spreadsheet reports, the formal design reviews, all formal documentation, the hands-on design and prototyping and testing of their systems, the team effort to integrate their PC boards, SolidWorks mechanical drawings, each student's completion and acceptance of their ASEE papers and Posters, the oral, individual finals taken each semester, each student's detailed Design Notebooks, and a final analysis of each student's weaknesses and strengths. A spreadsheet was made of all their points. Also shown in the table below is the grading rubric, Table 4, for last semester 3 hour Capstone class.

1	Design Notebook and Logbook (Depth and Breadth of project)	15%
2	Engineering Analysis, simulations, and ABET i-k proficiency	15%
3	ASEE Paper and/or Small Sat Paper/AHAC paper	10%
4	Your system maturity, Proto-flight fully working, Flight system	15%
5	Understanding, Calibration, test data, and Thermal/Vacuum testing	10%
6	Sustainability, ICDs, EDR Material for Summer Handoff	10%
7	Overall team work, class participation, field trip, and work ethic	15%
8	Your Creativity, Research, Problem Solving, Completeness, Details	10%

Table 4: Senior engineering capstone grading rubric

Some typical example quotes from alumni surveys include the following:

Graduate A: *For the past 15 years, the Physics and Engineering department has integrated a rare blend of theoretical rigor and practical application. At Taylor University, I learned "where there's a will, there's a way." I have found that this basic outlook on life is a prerequisite to becoming a successful entrepreneur, who must challenge the status quo and beat incumbents on a shoestring budget. In my days at Taylor University (1997 - 2001), we were pushing the limits of undergraduate education in a variety of categories. From space probes under contract to NASA, to building a solar racing car on 5% of the budget of our competitors, to the nanosatellite program, where our design was built around non-radiation hard*

componentry, my time at Taylor University was saturated with creative, entrepreneurial problem solving opportunity. Directly following graduation from LACU, I teamed up with Dr. Voss (Chair at the time) and student graduate (fellow 2001 Physics graduate) to create a new startup called NanoStar. Our collective goal was to commercialize the nanosatellite technology we built in the lab and deliver a store-and-forward communications system to the World. We pitched this concept to venture capitalists in six cities across the country and learned a great deal about how to design a robust startup in the process. These lessons undergird my current venture, MyFarms, which is going head-to-head with agricultural giant, Monsanto, to apply big data concepts to day-to-day farming practices and dramatically increase food production worldwide. My experience at LACU was truly transformational. I learned the core principles of managing science, technology and entrepreneurship; lessons that continue to serve me well each day."

Graduate B, *"TSAT has played a tremendous role in my career decision and has been a major stepping stone in adjusting to my current job. I am currently doing ECU development in the automotive industry, and working on TSAT gave me the flexibility of learning more about the academic side and the practical side of embedded systems"*

Graduate C: *My senior project was good preparation for the "real-world." The experience of going through the entire design process of developing a scope, working hard to make sure the project is successful, and presenting the final product is similar to what I do now. I think that having the freedom to develop an idea and also to fail is important. I have some specific tasks that I must complete, but a lot of my job requires taking the goals of my department and developing "projects" to fulfill those high level goals. I do not have a "professor" or boss telling me everything I need to do. Allowing students to develop their own "project" as long as it meets the high level requirements of the engineering curriculum is a good way to grow and develop engineers. The science building project that I worked on was not my original project. We had started a different one, and realized it really was not a feasible project midway into fall semester. This was good experience, because sometimes you need to be able to swallow your pride and admit that your original idea was not as good as it initially appeared.*

Conclusion

The University Nanosatellite Program and the senior engineering capstone class allow students the opportunity to develop a project with real-world scientific relevance. Student involvement in satellite design promotes creativity, ingenuity, and the development of vital engineering skills that are applicable to a wide range of engineering disciplines. The educational value of satellite design in a capstone course cannot be overemphasized.

Abbreviation and Acronym List

Note: some abbreviations not included

ADCS	Attitude Determination and Control System

AFRL	Air Force Research Labs
AFOSR	Air Force Office of Scientific Research
Cal Poly	California Polytechnic State University
CDR	Critical Design Review
CDH	Command and Data Handling
DSX	Demonstrations and Science Experiment
EAT	Expert Area Teleconference
EDR	Engineering Design Review
ELEO	Extremely Low Earth Orbit
EMI	Electromagnetic Interference
EPS	Electrical Power System
FCR	Flight Competition Review
GEARR-Sat	Globalstar Experiment and Risk Reduction Satellite
HARP	High Altitude Research Program
ICD	Interface Control Document
L-C	Likelihood-Consequence
LEO	Low Earth Orbit
LEP	Lightning-induced Electron Precipitation
PDR	Preliminary Design Review
PoC	Point of Contact
RVM	Requirements Verification Matrix
SHOT	Student Hands On Training (workshop)
SCR	System Concept Review
SRR	System Requirements Review
SSD	Solid State Detector
TEST	Thunderstorm Effects in Space and Technology
ThEEF	The Earths Electric Field
TRL	Technical Readiness Level
TSAT	Test Satellite Lite
UNP	University Nanosatellite Program
VLF	Very Low Frequency (light)
VPM	Very Low Frequency and Particle Mapper

Table 5: Abbreviation and Acronym List

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