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UNITE CubeSat: From Inception to Early Orbital Operations

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ABSTRACT

On January 31, 2019 the University of Southern Indiana UNITE CubeSat was deployed from the International Space Station and has transmitted data every day since. The missions of UNITE [Undergraduate Nano Ionospheric Temperature Explorer] are to measure plasma properties in the lower ionosphere using a Langmuir Plasma Probe, to measure its internal and skin temperatures to compare with a student-developed thermal model, and to track the orbital decay of the CubeSat, particularly near re-entry. The 3U UNITE CubeSat is passively magnetically and aerodynamically stabilized. This paper summarizes the design, build, integration, test and operations phases of the UNITE project since its inception in August 2016. The all-undergraduate team designed, fabricated, tested and integrated the command board, solar panels, and temperature sensor array. In addition, the team integrated a magnetometer and GPS. A commercially purchased Electric Power/Communication Subsystem provides Maximum Power Point Tracking and Simplex and Duplex communication through the Globalstar satellite network allowing nearly 24/7 contact with UNITE. The team wrote and tested the flight software which is divided into five primary modes. Some results from the first several months of flight are summarized and lessons learned are shared, with the intent of assisting future CubeSat teams.

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INTRODUCTION

The deployment of the University of Southern Indiana UNITE [Undergraduate Nano Ionospheric Temperature Explorer] 3U CubeSat from the International Space Station (ISS) on January 31, 2019 marked the culmination of nearly two and a half years of effort, and the beginning of a planned year and a half mission. UNITE is one of 23 NASA-funded USIP-2 [Undergraduate Student Instrument Project-2] CubeSat projects chosen in April 2016. UNITE was the first USIP-2 CubeSat deployed, and, as of early June 2019, it has been transmitting daily for just over four months.

The three mission objectives of UNITE are: (1) conduct space weather (plasma property) measurements in the largely unexplored lower ionosphere using a Langmuir Plasma Probe, (2) measure exterior and interior temperatures of the CubeSat for comparison with a student-developed thermal model, and (3) track the orbital decay of the spacecraft, especially just before re-entry, with the intent of updating CubeSat drag models.

The all-undergraduate team at the University of Southern Indiana (USI) has been responsible for the design, integration, testing, delivery and operations of UNITE. Team members have predominantly been engineering students, but physics students and a computer science student have participated, as well.

Following on the success of Taylor University's TSAT[1] CubeSat from 2014 and the NearSpace Launch produced GEARRS-1 and GEARRS-2,[2] UNITE adopted a number of technologies and components demonstrated on those flights. The most important of those technologies was the Globalstar Simplex (and Duplex) radio which allows 24/7 data transmission from the CubeSat through the Globalstar satellite network without the need of a ground antenna.

The paper will proceed as follows. The first section will cover the timeline of the design, integration and testing of UNITE through deployment. Following this will be a discussion of the Concept of Operations and then a system overview of UNITE. Next, in turn will be sections on the Mechanical, Command and Data Handling hardware, Communication, and Electric Power Subsystems. Then the Langmuir Plasma Probe, Temperature Sensor Array and Thermal Modeling, Attitude Control and Determination, and Global Positioning System will be discussed. The flight software and its testing will be described followed by a discussion of the present orbital status, lessons learned and some concluding remarks. Because of limited space, some aspects of UNITE will be more heavily emphasized than others. Future papers will cover certain subsystems in more detail.

NASA USIP REQUIREMENTS AND UNITE KEY EVENTS TIMELINE THRU DEPLOYMENT

The NASA USIP requirements provided a disciplined framework in which the UNITE project was accomplished. USIP required that: the CubeSat be no larger than 3U, the team only be composed of undergraduates (graduate mentors were allowed), the team be multi-disciplinary, four mandatory reviews be passed, and flight hardware be ready for delivery 18 months after the Project Initiation Conference. NASA USIP provided $200,000, and no restriction was placed on using other funding sources. A short summary of the timeline of the UNITE project through deployment is shown in Table 1.

Project Management from NASA's side was handled by Wallops Flight Facility (WFF). The mandatory reviews were done via WebEx, with the exception of the Critical Design Review (CDR) which the team chose to deliver in person at WFF.

A ten week internship, May 8 – July 14, 2017, by many of the team members allowed for continuing design and analysis work, CDR preparation, work with Engineering Design Units (EDUs) and preparation of Flight Unit hardware. Five and a half weeks of the internship were spent at USI, one week was spent in Virginia during which CDR was delivered, and the final three and a half weeks of the internship were spent onsite at the prime vendor, NearSpace Launch in Upland, IN.

The UNITE CubeSat arrived at full integration of flight hardware on Sunday October 8, 2017, but suffered a fire, apparently caused by incorrect wiring of a connector to the vendor's diagnostic port. The damage was largely limited to the Electric Power Subsystem (EPS), and a repaired unit was received from the vendor in early 2018. (UNITE's own diagnostic port was subsequently used for all interactions with the CubeSat.)

Following receipt of the repaired EPS and reintegration, bakeout and thermal vacuum testing, without solar panels was conducted, March 5 - 7, 2018 at Morehead State University's Spacecraft Environmental Testing Laboratory within the Space Science Center. Blank PCBs were substituted for solar panels because Kapton tape with silicone adhesive had been used as part of the solar cell placement rather than the acceptable acrylic adhesive Kapton tape. Bakeout of the solar panels occurred at the University of Illinois Urbana-Champaign Laboratory for Advanced Space Systems at Illinois (LASSI) on March 9 2018. Subsequently at LASSI, cg, mass moment of inertia, magnetometer and solar array tests were conducted.

Table 1: UNITE Timeline Through Deployment

Event	Date
UNITE USIP proposal submitted to NASA	November 20, 2015
USIP award announced	April 6, 2016
First UNITE team meeting	August 23, 2016
USIP Project Initiation Conferences	September 8, 12, 14, 15, 2016
UNITE Concept Review	November 17, 2016
UNITE Preliminary Design Review	February 24, 2017
10 week internship for most UNITE team members	May 8 – July 14, 2017
UNITE Critical Design Review at WFF	June 13, 2017
UNITE Flight Unit first integration and fire	October 8, 2017
Notification of manifest on ELaNa-21 with NanoRacks as the deployer	November 21, 2017
Bakeout and TVAC without solar arrays at Morehead State University	March 5 – 7, 2018
Bakeout of solar arrays at U. of Illinois Urbana-Champaign	March 9, 2018
Solar array and cg tests at U. of Illinois Urbana-Champaign	March 31, 2018
First regular tag-up with NanoRacks Cygnus NG-10 launch scheduled for November 21, 2018 with delivery set in late August/early September	April 5, 2018
Magnetometer, mass moment of inertia tests at U. of Illinois Urbana-Champaign	April 14, 2018
Soft-stow vibration test at ETS	April 17, 2018
FCC license applications submitted	May 17, 2018
Battery level vibration test of entire UNITE CubeSat at ETS	July 31, 2018
UNITE launch changed from Cygnus NG-10 to SpaceX CRS-16	September 5, 2018
UNITE Mission Readiness Review	September 14, 2018
Second soft-stow vibration test at ETS	October 1, 2018
FCC licenses received	October 2, 2018
UNITE delivered to NanoRacks, Webster, TX	October 17, 2018
UNITE launching on SpaceX CRS-16 to ISS	December 5, 2018
UNITE deployment from ISS	January 31, 2019

NanoRacks and NASA's Launch Services Program also provided an important framework of processes and documentation delivery dates during the 14 months leading up to deployment. Initially delivery of UNITE was set for the first week of July 2018. That was pushed to early September and finally to October 17.

NanoRacks required a vibration test to demonstrate the CubeSat could withstand the launch environment. Engineered Testing Systems (ETS) in Indianapolis kindly provided its vibration test facilities for this purpose at no charge to us on three occasions. The first "soft-stow" vibration test was conducted on April 17, 2018. Post-test, no debris was detected and all subsystems responded as expected during a lab test.

Subsequent to this, it was discovered that the already integrated battery pack had not undergone its own more stringent vibration test, which is part of the enhanced battery testing regime required of packs being handled by crew members on the ISS. It was deemed prudent to keep the battery pack integrated in the CubeSat and shake the entire CubeSat at the enhanced battery vibration level. This test was conducted on July 31, 2018, but a Schottky diode fell off the +X solar panel, and a small amount of debris, later found to be three 4-40 screws, was heard inside the CubeSat.

The CubeSat and its battery functioned normally in the lab following this test, but now UNITE had to be opened up for inspection, removal and replacement of the screws, and repair of the solar panel. As a precaution, the Schottky diodes on the remaining solar panels were also reattached. Once repairs were made, a second "soft-stow" vibration test was necessary, and was held on October 1, 2018 at ETS, which the CubeSat passed.

Following receipt of the FCC licenses on October 2, 2018, UNITE was delivered to NanoRacks at its Webster, TX facility on October 17, 2018. UNITE ended up being the only CubeSat integrated into its 6U length deployer.

CONCEPT OF OPERATIONS

The UNITE Concept of Operations was carefully planned taking into account the anticipated rate of orbital decay between deployment from the ISS and re-entry. Assumptions used in simulating orbital decay of UNITE are presented in Table 2.

Taking a deployment from ISS at 400 km as the baseline, and assuming the worst case of solar minimum, the mission duration is estimated, by simulation, to be 428 days. Most of those days will be in the F region of the ionosphere.

Power and data management were then factored in to develop a more detailed Concept of Operations. The Concept of Operations for UNITE is presented in Table 3, using the software operational modes. The mission length has been shortened to 405 days in the Concept of Operations.

Table 2: Assumptions for Orbital Decay Simulation

Parameter	Simulated Value
Solar Cycle	Solar Minimum
Orbit at Deployment	400 km, circular
CubeSat mass	4 kg
Average projected area	0.01501 m^2
C_D	2.2

Table 3: UNITE Operational Modes

Software Mode	Length, Altitude	Description
Startup	~ 1 hour, 400 km	Deployment from ISS, no communication permitted for at least 45 minutes, then 3 – 7 minutes for EPS health & safety packets
First Week	5 days (actual length was 9.75 days), 400 km	Intense data gathering
Interim	325 days, 400 – 325 km	Longest mode; instruments mostly dormant, tumbling slows
Stabilization	50 days, 325 – 300 km	Ram directed attitude achieved; increased magnetometer data gathering
Science	20 days, 300 – 225 km	Largest amount of data collection, all instruments sampling
Re-entry	5 days, 225 km to burnup	Highest intensity of data collection, all instruments sampling
Fallback	Anytime	Triggered by lack of Duplex and GPS; constant sampling rate; conservative data budget

UNITE CUBESAT SYSTEM OVERVIEW

In this section we give an overview of the UNITE Flight Unit. Table 4 provides a listing of the major components and their sources for the UNITE Flight Unit, followed by Table 5 which provides actual Flight Unit parameters.

NearSpace Launch (NSL) in Upland, Indiana was the prime vendor for the UNITE mission. Two NSL products in particular were key to the UNITE mission. The first was a Langmuir Plasma Probe, which had flight heritage from the TSAT and GEARRS missions. The second was the EPS/Comm which includes Maximum Power Point Tracking and, very importantly, the Globalstar Simplex and Duplex radios. Also included with this subsystem is a horizon sensor on the –Z face which prohibits transmissions when that face, housing the antennas, is pointing toward the Earth. In addition, the NSL system includes two rocker type deployment switches and a "solar enable" (light detection by solar arrays) that initiate the 45+ minute transmission silence prior to commencing operations.

Table 4: UNITE Flight Unit Component Sources

Component	Source
Anodized 6061 Aluminum Chassis	NearSpace Launch
EPS/Comm with Globalstar Simplex & Duplex, with horizon sensor (–Z Tx inhibit), deployment switches plus "solar enable", Maximum PowerPoint Tracking, Lithium polymer batteries	NearSpace Launch
Langmuir Plasma Probe and associated electronics	NearSpace Launch
HMC 2003 Magnetometer	Honeywell
B228 Magnets	K&J Magnetics
HyMu80 Cylindrical Rods	Mu-Metal
Magnet holder and HyMu80 rod holders	Student designed and fabricated
30 UTJ Solar Cells	SpectroLab
Solar Panel PCBs	Student designed, Sunstone Circuits fabricated
Command Board PCB	Student designed, Sunstone Circuits fabricated, student populated
PIC24FJ256GA106 microprocessor	Microchip via Digikey
GPS AsteRx-m	Septentrio via NSL
AD590 IC Temperature Sensors	Analog Devices via Digikey
Temperature Sensor Array PCBs, Magnetometer PCB, GPS PCB	Student designed, Sunstone Circuits fabricated

Most other components were TRL-9, but with the students choosing to take the risk of designing and populating the command board PCB (Printed Circuit Board), designing the solar panel PCBs and then applying all of the solar cells, and, as well, designing and populating PCBs for the magnetometer and the GPS. More details of these components and design efforts are given in the relevant sections of this paper. PCBs were designed at USI and prototyped in the PCB lab, but final fabrication of all PCBs was done by Sunstone Circuits.

The GPS was not in the original USIP proposal. The UNITE team secured extra funding for a GPS through the USI internal Endeavor Awards, as well as through an Indiana Space Grant Consortium grant.

Table 5: UNITE Flight Unit Parameters

Parameter	Value
Mass	3558 grams
Mass Moments of Inertia, taken at cg	I_{xx} = 0.0407 kgm^2 I_{yy} = 0.0394 kgm^2 I_{zz} = 0.0073 kgm^2 $I_{xy} = I_{yx}$ = +0.0000 kgm^2 $I_{xz} = I_{zx}$ = +0.0001 kgm^2 $I_{yz} = I_{zy}$ = -0.0003 kgm^2
cg location, coordinate origin at geometric center	x = -0.0005 m y = +0.0003 m z = +0.0158 m
Energy storage of LiPoly batteries	65.2 Whr
Simplex Tx frequency	1616.25 MHz
Duplex Tx frequency	1610 – 1625.5 MHz
Duplex Rx frequency	2483 – 2500 MHz
Langmuir Plasma Probe sweep range and rate	-4.5 V to +4.5V @ 1 Hz, reverse @ 1 Hz
Magnet (3x)	0.134 Am^2, each
HyMu80 rod (2x)	Remanence: 0.35 T, Coercivity: 1.59 Am^{-1}, Saturation: 0.73 T Volume: 174.18 mm^3

Finally, to complete this snapshot of the UNITE mission, we present two instances of orbital parameters available from the Two Line Elements (TLEs) posted almost daily on www.space-track.org by the 18th Space Control Squadron. In Table 6 are the parameters from the first TLE, posted within 24 hours of deployment, and the other from the end of the fourth month in orbit.

Table 6: UNITE Orbital Parameters

Parameter	@ Deployment	@ 4 Months
Inclination, deg	51.6408	51.6386
Apogee, km	405.676	403.5083
Perigee, km	401.2362	399.1247
eccentricity	.0003274	.0003233
RAAN, deg	287.6343	240.7415
Argument of perigee, deg	27.5597	321.0165

MECHANICAL SUBSYSTEM

The objective of the Mechanical Subsystem is to provide a 3U CubeSat structure, a CAD model, component placement, proper cg location, a mass budget, oversight of environmental tests and compliance with launch deployment system requirements. The Mechanical Subsystem lead was responsible for modeling the UNITE CubeSat in SolidWorks, as well as ensuring the final integration of the Flight Unit.

The 3U structure, purchased from NSL, is 6061 anodized aluminum. The mass of the fully integrated flight unit is 3558 grams. A mechanical block diagram of the components housed in and on the CubeSat is shown in Figure 1 at the end of the paper. Following this is Figure 2, a SolidWorks rendering of UNITE, and Figure 3, an exploded SolidWorks rendering of UNITE, both at the end of the paper. Notice the use of "optical benches" on which interior components are placed. Those benches allow for convenient "flatsat" testing and inspection of components outside the chassis.

COMMAND AND DATA HANDLING SUBSYSTEM

The objective of the Command and Data Handling Subsystem (C&DH) is to control the operating modes of the CubeSat, and interface with payload sensors and other subsystems by collecting sensor data through digital and analog processing, packaging the data and transmitting the data to the Communication Subsystem.

At the heart of the C&DH is the PIC24FJ256GA106 microprocessor which sits on a student designed command board with circuitry specially built to interface with the Temperature Sensor Array, magnetometer and Langmuir Plasma Probe.[7] In Figure 4, at the end of the paper, is a Functional Block Diagram showing the interactions of the microprocessor with various components. The student designed command board housing the microprocessor and other conditioning components is shown in Figure 5. More details about the command board design and testing will be provided in a later paper.

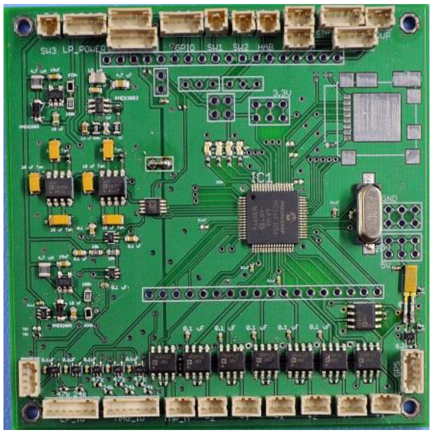


Figure 5: Student designed and populated command board

The flight software on the processor is in the C language. The student designed flight software has five nominal flight modes that will control instrument sampling rates as a function of altitude or mission time. Two additional contingency modes exist in case of mission anomalies. There is also a mode used only when the flight software is tested on the ground to allow for rapid transition between modes. Finally, two modes exist outside the C&DH, which are controlled by the EPS for initially turning on the vehicle once deployed, and for charging batteries when battery power becomes too low. The flight software will be described in more detail in a later section.

COMMUNICATION SUBSYSTEM

The objective of the Communication Subsystem (COMM) is to transmit any data (science and housekeeping) sent to it from C&DH to the Globalstar satellite constellation. That data is displayed by the online NSL Simplex or Duplex Console. Likewise, COMM will receive any SMS commands originally sent from the online Duplex Console, and relay those commands to C&DH.

The Communication Subsystem consists of a Simplex unit which only transmits, and a Duplex unit which can both receive commands and transmit data. Both units communicate via the Globalstar constellation of low earth orbiting satellites at 1414 km, making possible virtually 24/7 communications with the UNITE CubeSat.[1] This means the UNITE team has no need for any ground station antenna. Note that the Simplex unit is integrated with the Electric Power Subsystem control module. The COMM subsystem was purchased from NearSpace Launch.

The Simplex is a high-reliability unit operating in the 1600-MHz range at approximately 9 bytes per second. The radio acts as a broadcast-type unit, transmitting data regardless of the availability for downlink. Tests have shown that the Simplex can even successfully transmit data from indoors through doors and windows. The Duplex unit operates on an established-link system which allows for a transmission rate of 700 bytes per second. However, this speed is at the cost of reliability. To establish a link and successfully transmit a packet can take approximately one minute. This length of a lock necessitates a low rotation rate. Most satellites would seek to solve this issue by use of an active attitude control system. However, because of UNITE's monetary, time, weight, and power budgets, a passive system is used.

During ground testing, the Simplex used a patch antenna identical to that on the Flight Unit; however, the Duplex required a special, high-power, ground antenna to reach the Globalstar constellation. These tests showed that data could be sent through either unit and commands sent to the Duplex could be executed by UNITE. During tests of the stand-alone Flight Unit, the

Simplex made consistent contact, but the Duplex was not used due to the lack of antenna power.

Analysis was also performed on the series of communication links involved in UNITE's communication system. A link analysis was performed in an effort to understand the performance of the system. The link analysis was based on work performed in 2000 on the allocation of bandwidth for Globalstar.[6] The hand calculations performed on the Simplex downlink side found an output of the antenna on the receiving satellite to be -172.73 dBW. This analysis was also performed in STK using a link analysis tool. The results after factoring in the receiving antenna are an average of -171.0 dBW. The close results validate the hand calculations. The same hand calculations were used for both links between the Duplex and satellites, and both links between the satellites and ground station.

Additional analysis was performed on the effect of the Doppler shift on the communication system. The worst-case scenario was determined to be when UNITE and the Globalstar satellite are travelling either directly toward or away from each other. Either scenario would cause the largest change in the perceived frequency. The largest frequency shift was found to be 79.49 kHz for downlink communications and 123.0 kHz for uplink communications. STK was used to verify these results using UNITE's orbit as well as the orbits of the Globalstar satellites. The results of the simulation showed that the maximum downlink shift was 40.09 kHz and uplink shift of 61.80 kHz. These shifts are acceptable given the bandwidths of the communication channels.

Following deployment, UNITE made the expected contact following the approximate 55-minute wait. This helped to establish the functionality of the Simplex as well as the satellite in general. However, no contact has been established through the Duplex unit as of yet, and the unit has yet to be confirmed to turn on. This could be due to UNITE's rotation as well as many other factors.

ELECTRIC POWER SUBSYSTEM

The Electric Power Subsystem (EPS) will manage and monitor power throughout the CubeSat. The EPS control module is integrated with COMM's Simplex unit. The EPS unit was purchased from NSL.

Several iterations of an energy budget were produced as the design matured. Shown in Table 7 is the final energy budget for the worst case situation of solar cells at 103.4 ^{0}C, 22% end of life efficiency and the minimum number of cells pointed at the sun.

The EPS consists of Spectrolab Ultra Triple Junction (UTJ) solar cells, custom made printed circuit boards to hold the solar cells, four Lithium-polymer batteries and a control module from NSL providing Maximum Power Point Tracking. A total of 30 solar cells cover the four long faces of the 3U UNITE CubeSat.

Table 7: Worst Case Energy Budget, 103.4 ^{0}C, 22% EOL efficiency, min cells at sun

Mode	Consumption (WHrs/Orbit)	Production (WHrs/Orbit)	Net (WHrs/Orbit)
First Week	-3.49	+4.65	+1.16
Interim	-3.00	+4.65	+1.65
Stabilization	-3.02	+4.65	+1.63
Science	-3.42	+4.65	+1.23
Re-entry	-3.59	+4.65	+1.06
Fallback	-3.01	+4.65	+1.64

The PCBs for the solar panels were student designed and then fabricated by Sunstone Circuits. After receiving the printed circuit boards which would serve as the basis of the solar panels, the continuity of the boards was assessed from pad to pad to confirm the board design and construction. The panels had additional components added on the underside of the boards such as temperature sensors and diodes.

The individual solar cells were also tested to ensure that each was operating nominally. The voltage of each was tested beneath a halogen lamp, and visually inspected for cracks and defects. The next step was to prepare the solar cells for attachment to the boards. Common practice for solar cells is the attachment of the negative tabs of one cell to the positive back of the previous cell to create a string. For UNITE's panels, a different design was developed to maximize the number of cells in the limited space. To do so, the orientation was changed such that the negative tabs faced the midline of the board. The tabs were also cut short to place the cells as close as possible. Finally, the excess portions of the tabs were added to the positive back of the cell with silver epoxy to create a solder point for the panel.

The next stage was to attach the solar cells to the board creating the panel. The printed circuit boards were prepared by cleaning the surface with denatured alcohol and applying Kapton tape over the solder pads and areas that did not have solar cells. The cells were attached to the board with a thin layer of silicon RTV. The Kapton tape helped to act as an outline and level to screed the RTV off. Once the RTV was down, the solar cells were placed on top. It was important to keep the amount of entrapped bubbles to a minimum to prevent cracking of the cells under a vacuum. This was performed by keeping pockets from forming underneath the surface of the cells and by gently rocking the cells as they were being placed on the RTV until they were fully seated on the board. Once all cells on a panel were in place, the Kapton outlines were removed and the tabs were soldered to the board. The panels were then checked to confirm that voltages were nominal across all cells and strings. Figure 6 shows a UNITE team member preparing to attach the Spectrolab UTJ solar cells to its PCB panel.

Figure 6: Application of solar cells on solar panel

The next test of the solar panels was to characterize the I-V curves of each one. This test was performed at the University of Illinois Urbana-Champaign with their solar simulator. Each panel was individually tested while attached to a programmable load and digital multimeter. The current and voltage of each panel was read across a variety of loading scenarios to generate the curve. Only one anomaly was noticed during this test. The current in the +Y panel was twice that of the others. This is believed to be a result of the panel having a better voltage balance than the others. The diodes on the panels prevent current from flowing from one string to another if the one is at a higher voltage. This also prevents current from leaving the lower voltage string. The high current of the one panel is thought to be the result of both strings operating at near-identical voltages.

Orbital results of UNITE have shown no issues with the power system or solar panels. All data received from the Electric Power System has shown high battery voltages resulting from a net-positive power balance

LANGMUIR PLASMA PROBE

The objective of the Langmuir Plasma Probe is to conduct *in situ* measurements of electron density and electron temperature, as well as ion density in the lower ionosphere. This probe is the scientific payload of the UNITE CubeSat.

The UNITE Langmuir Plasma Probe (LPP), a non-deployable planar probe, was purchased from NSL and has a commanded voltage sweeping from -4.5 volts to +4.5 volts at 1 Hz, with higher sweep rates possible to probe possible sporadic E layers in the lower ionosphere. It can also be held at a static +4 volts and -4 volts to take measurements. The UNITE LPP has four calibration resistors that are utilized at the beginning and end of a voltage sweep. The probe can be seen on the +Z face of UNITE in Figure 2 at the end of the paper.

The Ionosphere

The ionosphere exists simultaneously with that part of the Earth's atmosphere extending from about 80 km to 1000 km. Less than 1% of the tenuous constituents of the atmosphere at those altitudes are ionized by UV and other short wavelength radiation from the Sun resulting in an ionized gas – electrons and positive ions – known as plasma[3]. The density and temperature of the plasma can vary not only with altitude, but also with latitude, time of day, season and condition of solar maximum or solar minimum. The state of the ionosphere has an impact on the propagation of radio waves at those altitudes.

The UNITE CubeSat is orbiting at altitudes of 400 km and below during its mission, so it will be in the thermosphere and simultaneously in the so-called F region of the ionosphere, with a transition to the E region only during the final few days of its time in orbit. *In situ* measurements of ionospheric plasma are rarely done in these regions on a global basis.

Langmuir Probe operations

The fundamentals of a Langmuir Plasma Probe, sometimes known simply as a Langmuir Probe, or electric probe, are described in Reference 5, where the description assumes in-lab operation. References 3 and 4 specialize Langmuir Probe functions to on-orbit sensing of ionospheric plasma.

In summary, a metal Langmuir probe is electrically biased (in the case of UNITE from -4.5 V to + 4.5 V) to collect electron and/or positive ion currents. The potential at which no net current is collected from the plasma is called the floating potential. However, even though the plasma is (or is assumed to be) electrically neutral, namely the electron and positive ion densities are equal, the much lighter electrons have a higher thermal speed causing the electrons to reach the probe more quickly than the heavier positive ions. This results in the floating potential being less than the plasma potential. This lower floating potential relative to the plasma potential retards electron collection while enhancing positive ion collection, again ensuring zero net current to the probe.

This biasing of the voltage from negative to positive (and back), and plotting of the current as a function of voltage, results in a characteristic I-V curve, an example of which is shown in Figure 7. The current from the probe to the plasma, namely electron collection current, is taken as positive.[3]

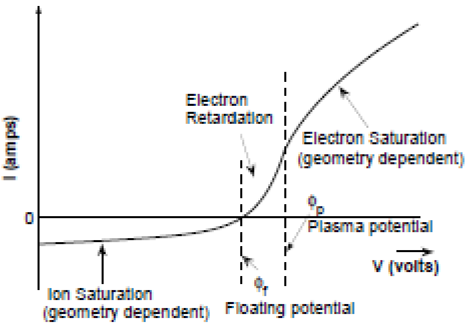


Figure 7: Typical Langmuir Probe I-V curve from Reference 3.

When the applied voltage on the probe is sufficiently negative with respect to the plasma potential then the ion saturation current is reached, where only ions are collected. At the other extreme, when the applied voltage is sufficiently positive with respect to the plasma potential, then the probe collects the election saturation current, where only electrons are collected. Because the electron mass is so much less than the positive ion mass, the electron saturation current will be much greater than the magnitude of the ion saturation current.

Practical Langmuir Probe Complications

Practical Langmuir probe complications relevant to operation on an orbiting spacecraft are discussed in References 3 and 4. Among those are the obvious violation of "saturation" as a result of the formation and expansion of a plasma sheath around the probe, the thickness of which is characterized by the Debye length.

Because the probe is finite in extent, rather than the infinite assumed in theory, a guard can be placed around the probe and driven at the same voltage as the probe to mitigate the effect of finite probe extent. The UNITE LPP has such a guard.

Further there is the need to include a probe surface with a uniform work function. In the case of the UNITE LPP, the probe surface has been gold coated. However, any contamination of the probe could cause "hysteresis" in the I-V curve, namely mis-match between the I-V curve generated as applied voltage sweeps up versus the curve generated from the down sweep of the voltage.

Barjatya and Auman point out the need to collect ion current to balance the electron current in the electron saturation region.[3, 4] Because the available ion current is more than an order of magnitude smaller than the electron current, a surface area on the spacecraft a 1000 times larger than the LPP area has to be available to collect the ion current. If such a collection area is not available, then the floating potential will be driven negative, violating the assumption of constant floating potential assumed for the analysis of LPP results.

Auman further points out that only ram directed ions can be collected for the above purpose of "closing the circuit."[4] (The ions' much lower thermal speed does not allow them to be collected in non-ram directed surfaces, as can the electrons with their much higher thermal speeds.) Thus, a sufficient area in the ram direction needs to be available to collect the ion current. The UNITE ram directed face, the +Z face, has in fact been coated with aquadag outside the small probe area, and in fact the ratio of conductive ram area, outside the probe rectangle, to probe area is 1200.

Langmuir Probe and UNITE Concept of Operations

In order to successfully measure the plasma properties, the Langmuir Plasma Probe needs to be "ram directed," i.e., facing in the same direction, or nearly the same direction, as the velocity vector. Because the UNITE CubeSat has only passive means of orienting the CubeSat in the ram direction, namely fins and a cg slightly displaced in the +Z direction, it is expected that February 2020 will be the earliest that a ram-directed orientation will be achieved. This ram-directed orientation should happen between 350 km and 300 km altitude. A later paper will detail the algorithm used to extract plasma parameters from the I-V curve generated from LPP orbital data.

TEMPERATURE SENSOR ARRAY SUBSYSTEM AND THERMAL MODELING

The objective of the Temperature Sensor Array Subsystem (TSA) is to provide temperature measurements at eight locations on and inside the UNITE 3U CubeSat. These temperature results will be compared with a thermal model.

The temperature sensors are AD590 integrated circuit sensors from Analog Devices. The AD590 works by acting as a high impedance, constant current regulator that passes 1µA/K. The AD590 datasheet specifies that the temperature sensors have a factory accuracy of +/- 5 ºC. However, testing showed all UNITE's AD590 temperature sensors to be within +/- 0.6 ºC. One sensor is placed near each of the six CubeSat faces with one on the command board and one on the magnetometer.

TSA Calibration

Originally, conversion equations for each AD590 temperature sensor were developed from the circuitry surrounding each sensor.[7] In testing it was found that the temperature reading was significantly higher than expected, particularly from the sensor on the magnetometer. For example, at room temperature (23 °C) the sensor detected temperatures close to 29 °C. This trend was found to happen for each other temperature sensor on UNITE with varying discrepancies. Therefore, it was deemed appropriate to calibrate the conversion equations to achieve a more accurate temperature reading.

Three sensors from three different locations were used to calibrate the equations: 1) the -X face sensor, 2) the +Y face sensor, and 3) the magnetometer sensor. At this point, UNITE was only partially disassembled, so the remaining temperature sensors were blocked from view and could not be used for calibration. UNITE was set to run and monitored using our ground software. When temperatures were reported through the software an IR thermometer was used to measure the actual temperature on each sensor. Room temperature was measured for 30 minutes to establish a base line. After 30 minutes, a heat lamp was used to heat each sensor and repeat the process as each sensor increased in temperature.

To achieve a direct comparison, the temperatures from both the ground software and the IR thermometer were plotted with respect to the ADC (Analog to Digital Converter) current value through each temperature sensor. As seen in Figure 8, this results in a linear relationship as well as a linear offset between the original conversion and the IR measurement. This pattern repeated itself for all three sensors used for calibration. A line of best fit on the IR measurement plot was used to determine a new conversion equation.

Originally, each sensor was to use its own, individual, conversion equation. However, a single equation was used in the final conversion for sake of time and lack of ability to test the remaining sensors. Also, due to coding constraints, the ADC value was required to be divided by 4. This resulted in a new equation being developed to use in our ground software as seen in Figure 9.

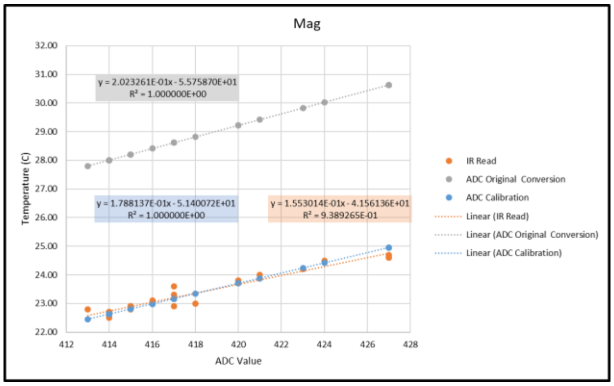


Figure 8: TSA calibrations

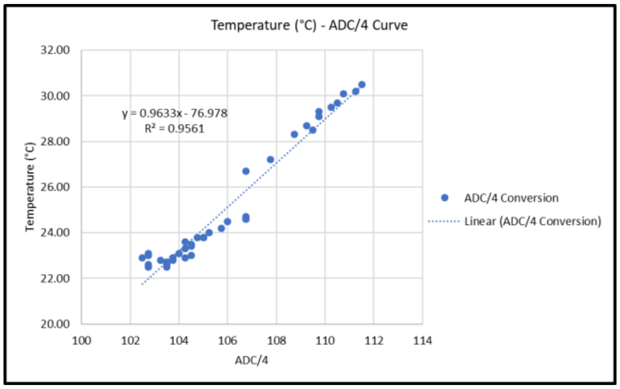


Figure 9: TSA final calibration

Calibrated In-Flight Data

After deployment from the International Space Station, UNITE was in First Week mode and was sampling at a high rate. Temperature sensor sampling was being done every 30 minutes and entire packets were being received almost every 2 hours. These packets contained the temperature samples for all operating sensors over the span of those 2 hours. The temperature fluctuations could also be compared to orbital position data. An example of data from First Week mode can be seen in Figure 10. This shows temperature readings from February 2, 2019. Each temperature sensor is represented by a different line. The green line at the bottom is due to the +Y face temperature sensor malfunctioning. It had stopped working prior to delivery to NanoRacks. There is also a 5-hour gap with no temperature readings. One assumption for this absence is that UNITE may have been "pointing" towards the Earth. In this case, transmission is not allowed therefore we would not have received any data. A table of minimum and maximum temperatures for 02/02/2019 can be seen in Table 8.

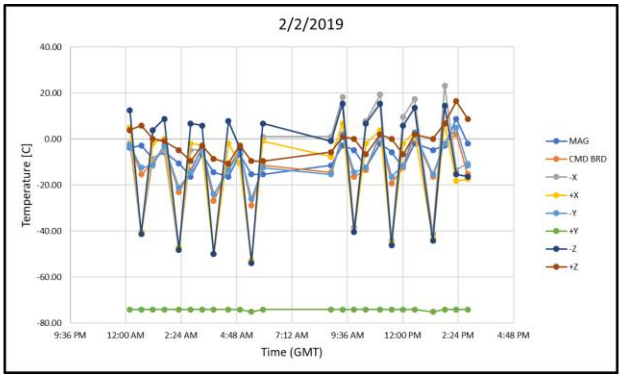


Figure 10: On-orbit Temperature Data, First Week Mode, February 2, 2019

Table 8: Minimum/Maximum Temperatures for February 2, 2019

Sensor Location	Min Temperature [°C]	Max Temperature [°C]
Magnetometer	-16.29	8.76
Command Board	-28.81	2.01
-X	-52.89	23.21
+X	-52.89	6.83
-Y	-25.92	4.90
+Y	N/A	N/A
-Z	-53.86	15.50
+Z	-10.51	16.46

Since entering Interim mode, UNITE has sampled temperatures over the last 4 months as seen in Figure 11. Samples during this mode are taken every 8 hours. There have been three instances in these 4 months where temperatures of all sensors read as the same, very low temperature (-76.98 °C). This is likely a data dropout. Another notable data point is on 05/19/2019. As seen in Figure 11, the temperature on the magnetometer spiked upward. In comparing that point with the other sensors, they also experienced this same phenomenon. An explanation for this is yet to be determined.

Thermal Modeling

A thermal simulation of the UNITE CubeSat has been completed using Thermal Desktop; the simulation indicates that the CubeSat will be within desired temperature limits during the mission.[8] Presently the team is working to adjust the thermal model parameters so the simulation results more closely match the on-orbit temperature measurements. Results of the adjustment of the thermal model will be presented in a later paper.

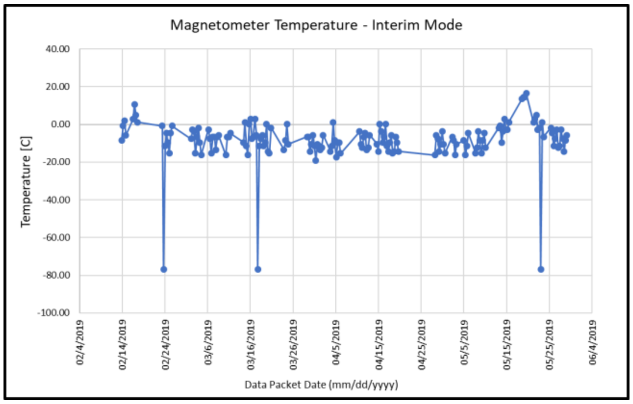


Figure 11: On-orbit magnetometer temperatures during Interim Mode

ATTITUDE CONTROL AND DETERMINATION SUBSYSTEM

The objective of the Attitude Control and Determination Subsystem is to stabilize UNITE in the ram direction and determine UNITE's attitude and attitude rates via an Extended Kalman filter using magnetometer data, and possibly other sources. The magnetometer is a Honeywell HMC2003 three-axis device. It is capable of measuring the magnetic field with a 4 nT resolution.

Aerodynamic stabilization is accomplished by placing the cg at 1.58 cm ahead of the geometric center of the CubeSat, and by including small fins on the rear of the CubeSat. In addition, Mu-Metal rods will dampen rotational rates about two axes simultaneous with aerodynamic stabilization. Simulation of aerodynamic and Mu-Metal assisted stabilization has been conducted using a Ray Trace Method and the online available tool SNAP (Smart Nanosatellite Attitude Propagator).[9, 12, 13]

In addition, a set of three magnets have been added inside the structure to allow the CubeSat to align with the magnetic field as the vehicle descends from 400 km to 300 km. These may assist in stabilizing UNITE and allow the Duplex antenna to connect with the Globalstar system early in the mission. At altitudes below 300 km, aerodynamic stabilization will take over from the effect of the magnets.

Details of the Extended Kalman Filter algorithms used to estimate attitude rates and attitude will be provided in a future paper.[11]

GLOBAL POSITIONING SYSTEM

The objective of the GPS (Global Positioning System) Subsystem is to provide position, velocity and time from which orbital elements can be determined in order to track orbital decay.

A GPS unit was not in the original UNITE proposal, but funding was secured to test an Engineering Design Unit GPS, and to include a Flight Unit GPS on UNITE. The Flight Unit GPS has the COCOM Limits disabled. The GPS unit is a Septentrio AsteRx-m secured through NearSpace Launch.

Initial GPS Trade Study Analysis

Once funding was secured for the GPS unit the UNITE team contacted our primary vendor, NearSpace Launch to determine potential products that could be acquired. The UNITE team was provided with three options: the Piksi Space GNSS, GlobalStar Stinger, and the NovAtel OEM4-2L GPS. It is important to note that the chosen hardware (Septentrio AsteRx-m GPS) was not listed in the initial GPS options provided to the UNITE team. Important GPS characteristics influencing selection for a CubeSat mission are shown in Table 9.

Table 9: GPS units initially considered

GPS	Mass (grams)	Operating Power (Watts)	Platform Code Source
Piksi Space GNSS	20	0.5	Open Source (C/C++)
GlobalStar Stinger	N/A	2.035	Proprietary
NovAtel OEM4-2L GPS	27	0.32	Proprietary

Based on this initial design trade the Piksi Space GNSS was selected due to its low operating power, low mass, and its code functionality. Once the Piksi Space GNSS GPS was selected the team performed extensive research for approximately 6 months to understand how its software would function with the command board. Unfortunately, NearSpace Launch notified the PI of UNITE that the GPS was no longer being manufactured and all support for that unit would cease to be available. Due to that issue, an alternative GPS, the AsteRx-m, was selected and procured by UNITE's vendor. Two GPS units were purchased, one, an Engineering Design Unit which was solely for verification and testing, and the other, a GPS with the COCOM limits disabled was placed in the Flight Unit.

GPS Setup and Initialization

Once the Septentrio AsteRx-m GPS was secured it was quickly determined that there was no peripheral cabling to interface with the GPS unit. Due to this issue a 30-pin I/O connector was developed, so the GPS could be programmed appropriately. The first printed circuit board broke out each of the 30 pins so rapid prototyping could be conducted. Once the team knew which pins would be used, the first PCB design (30 pin breakout board) was then wired to a USB connector, which was called the programming cable. The first iteration of the break out board being used as the programming cable is shown in Figure 12.

Once the programing cable was fully functioning, the GPS was connected to Septentrio's proprietary software suite called RxTools to program the GPS unit. For UNITE's mission the GPS was programmed to output the position, velocity, and time so the orbital elements could be back calculated.

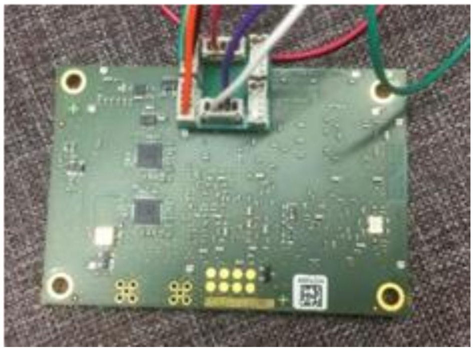


Figure 12: GPS Breakout Board

GPS Testing

Before the GPS was integrated into the CubeSat extensive testing was conducted with the EDU and then replicated on the Flight Unit to ensure it would work upon deployment. Some of the testing consisted of ensuring that the GPS could achieve a lock within the specified hot, cold, or warm start parameters, verifying that the GPS was outputting the correct data streams, and verifying that it could properly communicate with the command board through the RX/TX pins. Through all these tests the GPS was fully functional so the team integrated the unit into the CubeSat.

Once the GPS was fully integrated into the CubeSat the satellite went through environmental testing which included three vibration tests, and thermal vacuum testing. After each environmental test the basic functionality of the GPS was confirmed, but no outdoor tests to attempt lock were tried. Once the satellite was fully assembled (for the last time) the team made several attempts to obtain a lock; however, none were successful. The team eventually determined that the issue would remain unresolved because re-opening the satellite and reintegrating it could cause greater harm than good.

GPS On-orbit Results

Currently, the GPS unit has not obtained a lock with the GPS constellation; however, the GPS unit is functioning within the CubeSat. Even though the team is not receiving position, velocity and time data the GPS was programmed to send error messages when it cannot obtain a lock. Through the entire mission, the GPS has continuously provided the team with the error codes meaning it is functioning. It is speculated that the GPS's antenna is the root of the malfunction.

FLIGHT SOFTWARE

The core of the flight software is defined in the modes of operation. The modes of operation provide versatility to the UNITE mission and allow UNITE to maximize the amount of valuable science collected over the course of its mission. The software modes were carefully designed to take advantage of GlobalStar's connectivity while staying within a conservative data budget of $10,000, which was later increased.

Flight software modes

Startup Mode is an NSL EPS/Simplex mode designed to handle operations immediately after deployment. It begins with a 45-60 minute wait timer to prevent any transmissions in accordance with Nanoracks requirements. Next, the EPS/Simplex will beacon approximately 60 health & safety packets which will last anywhere from 3 to 7 minutes. Finally, the EPS/Simplex will set its busy line low, signaling the UNITE Command Board to begin its operations.

First Week Mode is what UNITE begins operating in. Once the beaconing from the EPS processor ends, UNITE initializes its internal communication protocols and timers. This mode was designed to last for 5 days, have high sampling rates, and send a relatively large amount of data packets. This mode provides a good gauge of the health of the CubeSat as each subsystem's data is sampled and transmitted frequently. The EPS processor also beacons at a higher rate during this period than it will for the rest of the mission.

Interim Mode is a UNITE Command Board mode designed to ensure all instruments are working consistently throughout the longest portion of UNITE's mission. In this mode, all instruments sample infrequently to prevent draining the batteries. UNITE remains in this mode until it descends to approximately 325 km.

Stabilization Mode is a UNITE Command Board mode designed to focus on gathering data mostly from the magnetometer. This mode will allow the ground team to determine UNITE's stabilization level as it approaches science mode using a ground-based Extended Kalman Filter. UNITE will remain in this mode from approximately 325 km down to 300 km where the core science of the mission will begin.

Science Mode is a UNITE Command Board mode designed to focus on UNITE's science mission. The Langmuir Plasma Probe will be heavily sampled during this time. UNITE will remain in this mode from 300 km to 225 km.

Reentry Mode is a UNITE Command Board mode designed to gather as much data as possible before UNITE burns up on reentry. UNITE will remain continually in this mode once it reaches 225 km; once it enters below 200 km, only a day or hours may be left of its mission.

Fallback Mode is a UNITE Command Board mode designed to maintain a constant stream of data sampling and collection from all instruments in the case of important system failures. This mode is a last resort if both of UNITE's means for determining its progress in the mission, the Duplex and the GPS, fail. All instruments are sampled at regular intervals to fulfill UNITE's data budget without regard to altitude.

Low Power Mode is an NSL EPS/Simplex mode designed to prevent UNITE critically draining its batteries or from going power negative. In this mode, the EPS/Simplex will successively turn off power switches 5 to 2 to conserve power regardless of power packets received. The EPS/Simplex will focus on recharging the batteries.

Diagnostic Mode is a UNITE Command Board mode designed to print out status information to the UNITE ground station during testing. This mode will never be triggered on orbit as it must be turned on manually in the source code. The diagnostic logs printed in this mode are stored on the UNITE ground station to be read and interpreted later.

Safe Mode If any major errors in software or system malfunctions preventing normal operation occur, UNITE will reset to safe mode. Once UNITE is in safe mode, a backup on-board clock will attempt to reinitialize UNITE to the correct mode based on a combination of time data and altitude data from the Duplex and GPS respectively.

Mode switching will only be able to occur in one direction (i.e. from First Week to Interim to Stabilization to Science to Reentry) which will prevent UNITE from backtracking due to fluctuations in GPS altitude readings. The mission clock will trigger a mode change after a certain period of time if the GPS does not gain lock or update UNITE's current altitude properly.

UNITE will not be implementing a data storage capability beyond the RAM on the command board's microcontroller. A sizeable queue will hold any data ready for transmission until it can be sent through either the Simplex or Duplex.

Flight software testing: EDU and Flight Unit

The flight software for UNITE has been interfaced, integrated and tested with almost every other subsystem that has an EDU unit. The flight software's main source control is handled via GitHub and the project can be found at: https://github.com/USIspace/UNITE-Spacecraft.git. The software has two main branches, a Master and a Development Branch which are defined in Table 10 below.

Table 10: Software branches

Branch Name	Description
Master	Latest working copy of the software without bugs or unfinished code blocks
Development	New, untested, or unfinished code blocks; Use this branch to add new features or interface new subsystems; Merges into the master branch when stable

Next we describe the various software tests used in the UNITE project.

1. Analog to Digital Converter Testing

Most of UNITE's instruments (e.g. the Langmuir Plasm Probe, temperature sensors, and magnetometer) are sampled by reading an analog output, a voltage, from the instrument's pins. To read that signal and transmit it as useful data, C&DH had to implement an Analog to Digital Converter (ADC). The ADC was tested with the temperature sensors, magnetometer, and Langmuir probe circuit and proved very accurate. During initial testing with both the temperature sensors and magnetometer, the ADC values for voltage outputs were compared with oscilloscope readings and the two values matched with high accuracy.

2. UART Testing

UART is one of the main communication protocols C&DH implements. The EPS/Simplex, Duplex, and GPS units all use this protocol to receive data from and send data back to C&DH. EPS/Simplex and Duplex EDU and Flight Units have been tested with this protocol to transfer data back and forth as well as transmit data through Globalstar and back to the ground. Each time, the data matched the data sent from C&DH exactly. Before receiving the specific GPS unit for UNITE, a GPS with similar communications protocols was tested with UART and proved very successful. Data was collected and parsed correctly, and, as well, the satellite mode updated based on the GPS's current simulated altitude. Once the Septentrio GPS was received, it was also tested via the UART protocol although using a proprietary message format with successful results.

3. SPI Testing

The SPI protocol will only be used for the Langmuir Plasma probe subsystem on UNITE. A main part of sampling probe data is to sweep the input voltage of the probe from a negative voltage to positive and back. To accomplish this, C&DH sends a digital value representing a voltage via SPI to a Digital to Analog Converter (DAC) circuit which reads a digital number and outputs its corresponding voltage. C&DH's SPI functionality was first tested using an oscilloscope, and its reading matched the expected value from C&DH each time. Once the DAC circuit was integrated into the Command Board, its output was also tested via the SPI protocol. All one hundred individual sweeping voltages from -4.5 V to +4.5 V proved accurate when connecting the DAC to a multimeter.

4. Day in the Life Testing

Starting with EDU components and then moving on to flight components, Day-in-the-Life (DITL) tests remained the standard means of testing the system. DITL tests checked whether the flight software logic performed as expected, whether the EPS/Simplex power switches were power cycling correctly, and whether the data collected from the ADC and UART devices was accurate. This data was saved to a digital log which provided a record of the tests' progress and results. In the EDU testing phase, the EDU EPS/Simplex was always powered through an external power source rather than through the solar panels which were not completely fabricated and integrated until the Flight Unit testing phase. The external power source mimicked a solar panel input and provided current information which became an indicator for UNITE's health and state (i.e. beaconing, transmitting, or idle). Although DITL tests usually lasted for 24 hours, UNITE's EDU tests ran anywhere from 2 to 72 hours often running overnight to check for runtime software logic errors.

In the Flight Unit testing phase, DITL tests were more refined and tended to run for at least a day if not longer. These tests focused on calibrating flight sensors like the temperature sensors and magnetometer and verifying flight software failure modes functioned properly. In addition, DITL flight testing was used to "test as you fly" checking that the modes of operation functioned as they would on orbit as well as testing the capabilities of UNITE's power system, solar panels, and batteries. Near the end of functional testing, UNITE was setup to run on its own, disconnected from external power. A halogen light provided power to the solar panels which charged UNITE's flight batteries, tripped the EPS/Simplex solar enable following release of deployment switches, and initiated flight software execution.

5. *Stress Testing*

Stress testing was a secondary means of testing UNITE and usually involved focusing intensely on the capabilities and limits of one subsystem at a time. In EDU stress testing, the EDU command board would be integrated with only one instrument subsystem, sampling it at higher frequencies than it would on orbit. Stress testing often exposed errors in software designed to sample, package, and transmit an instrument's data or faults in hardware designed to connect C&DH or power with the instrument subsystem being tested.

In Flight Unit stress testing, the flight software's limits were tested with a completely integrated flight unit. In these types of stress tests, the internal mission clock was accelerated which increased the rate at which C&DH had to sample, process, and power cycle all connected instruments. Flight stress tests aimed to check for interference between instruments when powered and sampling almost simultaneously. In addition, system stress testing involved running the flight software for multiple days continuously to improve the longevity of the flight software and catch time-specific or delayed logic errors.

On orbit behavior of the flight software

Fifty-five minutes after deployment, UNITE transmitted its first beacon through the GlobalStar network, and almost two hours later it transmitted its first data packet. UNITE then initialized into First Week mode although its mode change packet was lost in transmission. For four and a half days UNITE operated as expected in First Week mode's five day duration, sampling and transmitting each of its instrument's data packets regularly. However, on February 5th, UNITE transmitted a mode change packet, and instead of the expected "interim" message, the packet message was "first week". This indicated that a software error had occurred onboard UNITE which caused it to perform a hardware reset. After the reset, UNITE reinitialized into First Week mode, sent the mode change packet and resumed operation. Five days later it completed First Week mode and transitioned into Interim mode on February 10th as expected although the mode change packet was again lost in transmission. Since then, UNITE has been operating without issue or reset for 4 months in Interim mode.

UNITE can transmit six different kinds of data packets beside beacons as shown in Table 11. Subsequently we present details on some of these packets. Packets always begin with the vendor's own one-byte header followed by UNITE's own custom data packet. Each of these custom packets begins with a two-byte header in addition to the vendor's which includes a packet number identifier (4 bits) and mission clock timestamp (12 bits). The packet identifier corresponds to the packet type, and the timestamp gives the time of day in minutes from the mission clock's origin point. Since the mission clock origin was last set when UNITE reset, February 5th at 3:56 UTC is the mission clock's origin, and so the timestamp of each packet starts its count every day at 3:56 UTC.

Table 11: Data Packet Type and Numerical Identifier

Data Packet Type	Identifier
Satellite Mode	7
Langmuir Probe	1
Magnetometer	2
Temperature Sensor Array	3
GPS	4
Housekeeping	5

1. *Satellite Mode Packet*

Satellite mode packets were designed to alert the ground team when UNITE transitions from one mode to another. The satellite mode packet structure is very straightforward. After the initial header, each byte represents an ASCII encoded character of the alphabet. Each mode packet contains a string of characters representing the new satellite mode. Thus, an example satellite mode packet for First Week mode is shown in Figure 13 at the bottom of the paper.

2. *Magnetometer Packet*

The magnetometer data sample size is the smallest at three bytes but has the longest sampling duration. Eleven magnetometer samples can fit into one data packet. The magnetometer data packet structure is defined in Table 12 below.

The default magnetometer behavior is to sample every 10 seconds for an entire orbit at a time. This sample will only need to be taken a few times in flight to determine if UNITE has fully stabilized. The magnetometer also utilizes the ADC to convert voltages to 10-bit digital values. Like with the Langmuir Probe however, the magnetometer values are bit shifted two bits to the right (divided by four) to reduce each value to a byte for transmission.

Table 12: Magnetometer Packet

Position	Data	Size	Type
0-1	Header	2 bytes	
2,5,8,11,14,17,20,23, 26,29,32	X-axis voltage	11 bytes	unsigned integer (uint8)
3,6,9,12,15,18,21,24, 27,30,33	Y-axis voltage	11 bytes	unsigned integer (uint8)
4,7,10,13,16,19,22,25, 28,31,34	Z-axis voltage	11 bytes	unsigned integer (uint8)

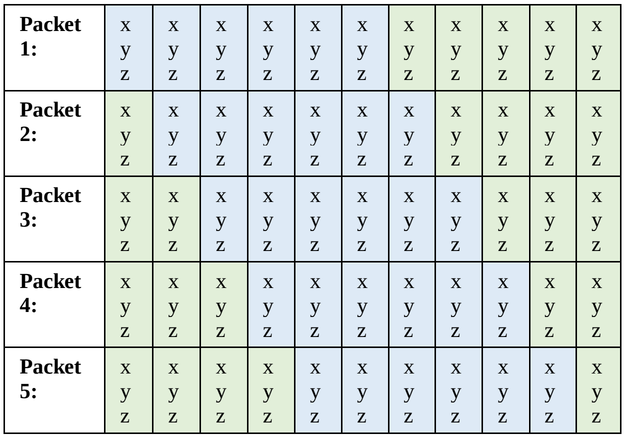
Since the magnetometer is sampled at regular intervals of 10 seconds, its data can be used with an Extended Kalman Filter to determine UNITE’s attitude and attitude rates on orbit. However, since data packets are often lost in transmission or delayed by a large downlink, magnetometer samples can be difficult to properly timestamp. Thus, we discuss further how to properly timestamp magnetometer samples.

There are three main issues when trying to timestamp magnetometer data samples. First, the main flight software loop executes once every minute to check whether data packets are ready for transmission. If a large number of packets are ready for transmission, it can delay the next magnetometer samples by longer than 10 seconds. Second, the magnetometer is different from other instruments in that the last sample in the packet does not necessarily correspond in the same way to the time the packet was received. Third, since magnetometer packets do not contain a sequence identifier, it can be difficult to determine if a packet was lost in transmission.

The above issues can be accounted for by carefully analyzing the pattern of magnetometer packets received and checking them against expected output.

Table 13 shows the first five magnetometer packets where each cell represents three bytes of data, one byte for each axis. The alternating blue and green highlight represents different main loop cycles. Each block of highlighted cells in the same color was taken between the same two main loop cycles.

Table 13: Magnetometer Packet Structure



Packet 1:	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z
Packet 2:	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z
Packet 3:	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z
Packet 4:	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z
Packet 5:	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z	x y z

Since the main loop executes every 60 seconds, 6 magnetometer samples are taken between each execution of the main loop, and one magnetometer packet is filled and ready for transmission every 110 seconds. Although a packet is filled and ready, it must wait until the next execution of the main loop before it is transmitted which causes a short delay anywhere from just under 10 to almost 60 seconds. Also, any delay in sampling due to transmissions will occur between the blue and green blocks. Thus, to timestamp a particular sample in a magnetometer packet, the packet’s position in the sequence is vital. As a quick example looking at packet 3, the second sample in packet 3 was taken approximately 120 seconds before the packet was transmitted which is equivalent to 90 seconds of more sampling to fill the packet plus a 30 second delay before the main loop executed again to transmit it.

3. *Temperature Packet*

The temperature sensor array data sample size is eight bytes long which repeats four times in one packet. The 10-bit ADC values for each sensor are divided by four to scale their sizes down to one byte. The temperature sensor data packet structure is shown in Table 14.

Table 14: Temperature Packet

Position	Data	Size	Type
0-1	Header	2 bytes	
2,10,18,26	Temp Mag	4 bytes	unsigned integer (uint8)
3,11,19,27	Temp –Z	4 bytes	unsigned integer (uint8)
4,12,20,28	Temp –Y	4 bytes	unsigned integer (uint8)
5,13,21,29	Temp –X	4 bytes	unsigned integer (uint8)
6,14,22,30	Temp +Z	4 bytes	unsigned integer (uint8)
7,15,23,31	Temp +Y	4 bytes	unsigned integer (uint8)
8,16,24,32	Temp +X	4 bytes	unsigned integer (uint8)
9,17,25,33	Temp Cmd. Board	4 bytes	unsigned integer (uint8)
34	unused		

Since the temperature sensor packet has 4 sets of data, the time of each data sample must be calculated from the packet's timestamp and the current sample rate

The equation to determine the time for each temperature dataset is shown below:

time = timestamp – (4 –dataset packet index)(sample rate)*

GROUND SUPPORT EQUIPMENT

The UNITE Engineering Design Unit and Flight Unit were constructed, integrated and tested largely in the Optics Laboratory of the Business and Engineering Center at USI. One 8' x 4' optical bench was used as dedicated work space with overflow to a second bench as needed. Two vertical cabinets were used to store components as they arrived.

A clean flow hood was designed and constructed as a Senior Design project in spring 2017 to support the build, test and integration of UNITE flight hardware.[10] The flow hood initially tested at ISO 4 cleanliness level in the central work area without equipment, and at ISO 5 with equipment. Figure 14 shows Flight Unit integration in the clean flow hood.

Figure 14: UNITE integration in clean flow hood

ORBITAL STATUS OF FLIGHT UNIT

As of May 31, 2019, the UNITE CubeSat has been operating in orbit for four months and is still tumbling. Table 15 shows the orbital status of the components on UNITE.

LESSONS LEARNED

The UNITE team had good intentions about configuration management from the beginning, initially adopting Orange Scrum as a configuration management tool. However, the team rather quickly gravitated to simply using Google Docs (and Github for software) to maintain and share documents. Unfortunately, with the loss of personnel through graduation, less time could be spent by the remaining members to generate and maintain documentation of written assembly procedures and photo documentation of the assembly steps. Thus the lack of recruitment of sufficient replacement personnel had a negative impact on the effort.

Table 15: UNITE Flight Unit Status

Component	On orbit status as of May 31, 2019
Software Mode	In Interm Mode after autonomously transitioning from First Week Mode on February 10, 2019
Temperature Sensor Array	All working except +Y solar panel sensor
Magnetometer	Working
Langmuir Plasma Probe	Working
GPS	Working, but position, velocity, time lock not expected
Simplex	Working
Duplex	No data has been received via the Duplex; one command has been attempted thru the Duplex, but was never acknowledged

Also complicating the project was inconsistent communication, documentation and follow-through on the part of the vendor. This included lack of complete testing of the battery pack to NanoRacks specification, confusion as to how the FCC license was to be handled, and confusion as to how their diagnostic port was to be used.

The team inadvertently used silicone-based adhesive Kapton tape as opposed to the acrylic-based adhesive tape. Silicone adhesive can ruin vacuum pumps on some thermal vacuum chambers. Confusion about the availability of liquid nitrogen at the site of thermal vacuum testing meant that UNITE was not tested against lower end temperatures expected on orbit. Also, the GPS should have been tested for lock after TVAC and each vibration test, rather than having lock tested just before delivery.

At the urging of the vendor a set of three small magnets were included in UNITE to assist aligning the CubeSat during the early part of the mission, with the intent of stabilizing it enough to achieve Duplex lock. It is not clear that such a stabilization will be achievable. It was also discovered too late that the magnets had a deleterious impact on the calibration curve of one axis of the magnetometer. Also, it was discovered late in the process that magnetometer data sampling could be inconsistent, making the magnetometer data difficult to use in any routine estimating attitude and attitude rates. Early on the decision was made to use ADC/4 data rather than full ADC data to help save on data costs. By the time it was realized there would be enough funds for full ADC data the changeover was not able to be successfully accomplished in the software.

CONCLUSION

The UNITE CubeSat has the distinction of being the first USIP-2 CubeSat deployed in space. UNITE is also the University of Southern Indiana's first spacecraft, and, in fact, UNITE is the first spacecraft produced and flown by a public institution in the state of Indiana.

NASA took a risk in funding undergraduate-only teams to design, build, integrate, test, deliver and operate CubeSats in Earth orbit. Students at the University of Southern Indiana rose to the challenge and executed the USIP-funded CubeSat project at a level that resulted in a CubeSat that has been operating in orbit for just over four months. The discipline of the NASA Systems Engineering approach, a comparatively simple CubeSat design without deployable elements, and some very capable students made possible what success UNITE has achieved.

This paper has summarized the major events of the project from inception to deployment. Some initial orbital results from the Temperature Sensor Array have been presented. All subsystems have been touched upon in the paper, some in more detail than others. The flight software received extended focus. Later papers will cover the Langmuir Plasma Probe I-V curve analysis equations, the Attitude Control and Determination Subsystem, and the Command and Data Handling hardware in more detail.

Acknowledgments

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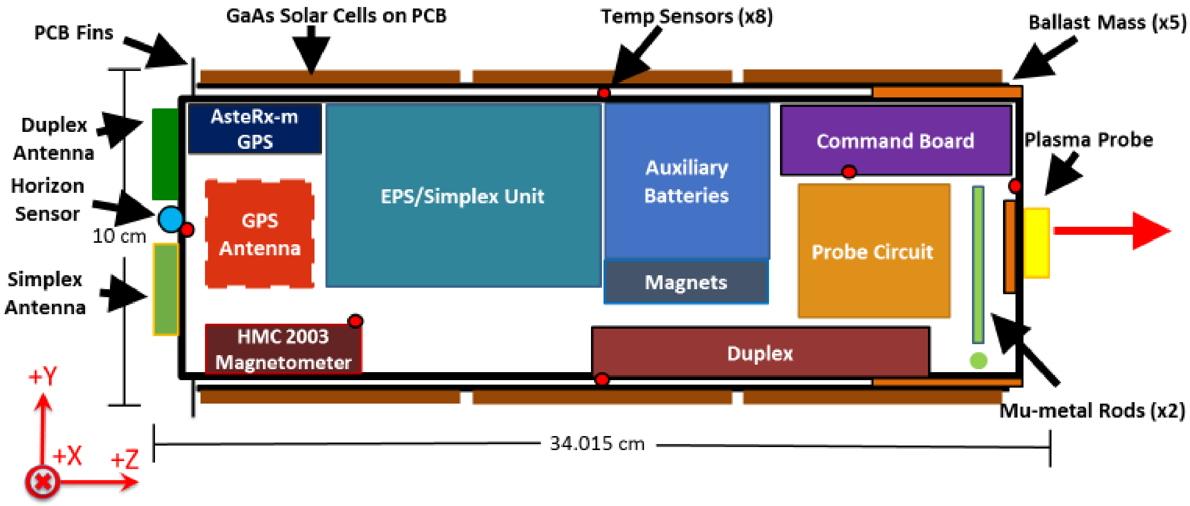

Figure 1: UNITE Mechanical Block Diagram

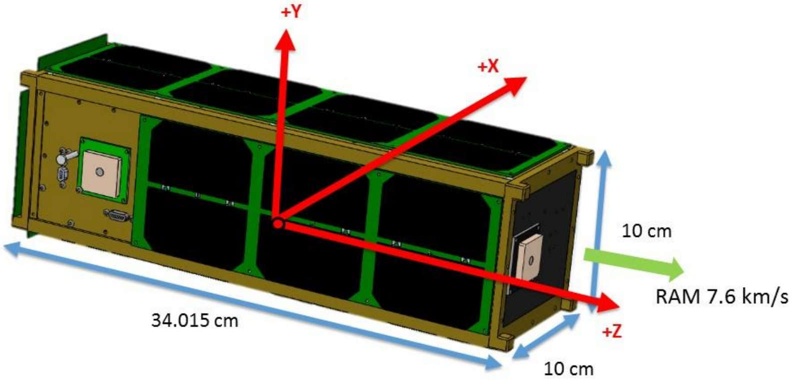

Figure 2: UNITE SolidWorks Rendering

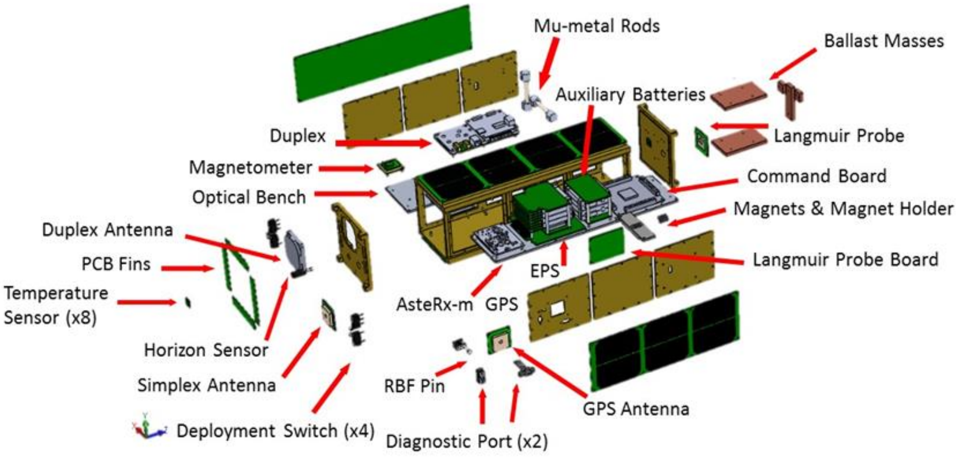

Figure 3: UNITE SolidWorks Exploded Rendering

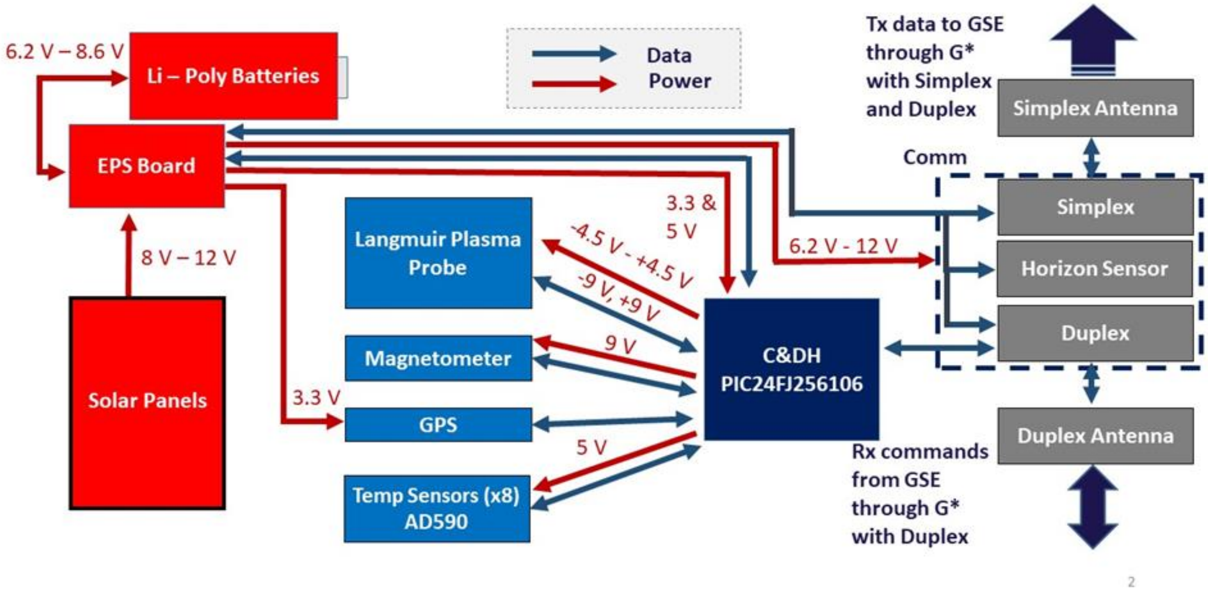

Figure 4: UNITE Functional Block Diagram

Packet**:**

A17000**4669727374205765656B**0000000000000000000000000000000000000000000000 (message data in bold)

Data	46	69	72	73	74	20	57	65	65	6B
Message	f	i	r	s	t		w	e	e	k

Figure 13: UNITE Packet Example